Postharvest application of edible coatings to reduce quality losses and prolong shelf life in plums

by

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DECLARATION

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Date: December 2019

SUMMARY

The Japanese plum (*Prunus salicina* Lindl.) is one of the most popular stone fruits consumed worldwide, characterised by its distinctive taste and high nutritional value. However, postharvest losses limit the economic value of exported plums, with the long handling chain of export and sale often resulting in shrivel, overripeness and decay. Whilst postharvest technologies such as low temperature storage and high density polyethylene (HDPE) bags are used to delay ripening and minimise moisture loss in exported plums, the incidence of fruit rejection on account of quality-related issues is still unfavourably high.

Edible coatings have been widely reported to maintain postharvest quality in fresh produce. Coatings form a semi-permeable barrier on the fruit surface that controls moisture loss and gaseous exchange, consequently delaying ripening and extending shelf life. This study aimed to investigate the potential of edible coatings to improve the export quality of plums by controlling postharvest losses and extending shelf life. In a laboratory-scale trial, six edible coatings, four of which were experimental (alginate, chitosan, gellan gum and gum arabic) and two commercial (High shine and Sta-fresh), were screened during a simulated shipping period (-0.5 ± 2°C and 90 ± 5% RH for five weeks) and a subsequent shelf life period (20 ± 2°C and 80 ± 5% RH for 20 days) using 'African Delight™' plums. Gum arabic performed best out of all the coatings. At 20 d shelf life, weight loss was significantly ($p<0.05$) reduced from 23.62% in control plums to 5.36% in plums coated with gum arabic. Similarly, shrivel was significantly ($p<0.05$) reduced from 9.56% (control) to 4.91% (gum arabic), and decay was significantly ($p<0.05$) reduced from 7.57% (control) to 1.19% (gum arabic) at 20 d shelf life. Additionally, plums coated with gum arabic exhibited a delay in physico-chemical changes during storage, such as fruit softening, loss of acidity and darkening of the peel colour. These changes were delayed as a result of suppressed respiration and ethylene production, which consequently reduced the rate of fruit ripening. At 20 d shelf life, plums coated with gum arabic resembled control plums at 5-10 d shelf life, indicating an extension of shelf life as a result of coating application. Furthermore, a volatile analysis confirmed that coating application did not result in the formation of off-flavours.

In order to validate the commercial viability of coating application and optimise coating formulation, gum arabic (GA) based coatings, including GA 2%, GA 5%, GA 10%, GA 5% + pomegranate seed oil and GA 5% + ascorbic acid, were applied to 'African Delight™' plums in a commercial packhouse. Commercial pack lines are generally equipped with atomizers to apply postharvest solutions such as fungicides; therefore, coating application on a commercial-scale is highly viable and would not require additional infrastructure. Fruit were subjected to real-life postharvest handling practices, and quality was assessed during a simulated shipping period (-0.5 ±

2°C and 90 ± 5% RH for six weeks) and a subsequent shelf life period (20 ± 2°C and 80 ± 5% RH for 15 days). The best performance was achieved with GA 10%, which resulted in a significant delay in physico-chemical changes during storage such as fruit softening, loss of acidity and darkening of the peel colour. These changes were delayed as a result of suppressed respiration and ethylene production, which consequently reduced the rate of fruit ripening. Plums coated with GA 10% were described by a trained sensory panel during descriptive sensory analysis as having unripe to semi-ripe sensory attributes at 5 d shelf life, compared to control plums which were characterised with a ripe to overripe sensory profile. This suggests that GA 10% could extend the shelf life of 'African Delight™' plums beyond the current five day end point of commercial sale. This observation was confirmed in the instrumental measurements, where fruit coated with GA 10% retained firmness (14.04 N), peel colour (L* = 34.67 and *h*° = 6.37) and TSS (15.60 °Brix) after 15 d at shelf life conditions. No off-flavours were detected in the sensory analysis as a result of coating application. Plums coated with GA 10% were also found to be microbially safe at 5 d shelf life, with no faecal coliforms detected and total coliforms falling within specified limits. Furthermore, coatings exhibited potential as a green replacement technology for HDPE bags. No significant difference ($p \geq 0.05$) in respiration rate was observed between coated fruit packed without HDPE and control fruit packed with HDPE bags at the end of cold storage. Thus, coatings may have created a similar modified atmosphere in plums as that created by the HDPE bags within the carton, which resulted in comparable physico-chemical changes during cold storage. Although the commercial viability and technological readiness of GA 10% as a postharvest edible coating is limited in this study, the use of gum arabic in postharvest edible coating application is promising.

OPSOMMING

Die Japanese pruim (*Prunus salicina* Lindl.) is een van die mees gewildste steenvrugte in die wêreld, as gevolg van die vrug se aangename smaak en hoë voedingswaarde. Ongelukkig is na-oes verlies ‘n groot uitdaging in uitvoerpruime met lang stoor periodes, soos verrimpeling, oorrypheid and bederf. Alhoewel na-oes tegnologie soos koelopberging en Hoë Digtheid Poli-Etileen (HDPE) sakke reeds gebruik word om die rypwordingsproses en vogverlies te vertraag, is die gehalteverlies steeds ongunstig hoog.

Daar word wyd berig dat eetbare bedekkings die na-oes kwaliteit van vars produkte onderhou. Hierdie bedekkings vorm 'n semi-deurlaatbare versperring op die vrugoppervlak wat vogverlies en gaswisseling beheer. Gevolglik word rypwording vertraag en die rakleeftyd verleng. Die doel van hierdie studie was om die potensiaal van eetbare bedekkings te ondersoek om die uitvoergehalte van pruime te verbeter en die rakleeftyd te verleng. Ses eetbare bedekkings waarvan vier eksperimenteel was (alginaat, chitosan, gellangom en arabiese gom) en twee van kommersiële oorsprong was (High shine en Sta-fresh) is op laboratoriumskaal beproef tydens ‘n gesimuleerde versendingstydperk (-0.5 ± 2°C en 90 ± 5% RH vir vyf weke) en daaropvolgende rakleeftyd (20 ± 2°C en 80 ± 5% RH vir 20 dae). ‘African Delight™’ pruime was gebruik om die proef uit te voer. Arabiese gom het die beste in vergelyking met die ander bedekkings presteer. Op 20 d rakleeftyd was gewigsverlies beduidend ($p<0.05$) verminder van 23.62% in kontrole pruime tot 5.36% in pruime wat met arabiese gom het bedek was (5.36%). Soortgelyk aan bogenoemde was verrimpeling beduidend ($p<0.05$) verminderd vanaf 9.56% (kontrole) tot 4.91% (arabiese gom) en bederf beduidend ($p<0.05$) verminderd vanaf 7.57% (kontrole) tot 1.19% (arabiese gom) op 20 d rakleeftyd. Bowendien het pruime wat met arabiese gom bedek was ‘n vertraging in fisisie-chemiese na-oes veranderinge ervaar, soos ‘n afname in fermheid, ‘n verlies in suurheid en ‘n verdonkering van skilkleur. Hierdie veranderinge was vertraag as gevolg van ‘n laer respirasie tempo en etileenproduksie wat gevolglik die tempo van vrugte-rypwording verlaag het. Pruime wat met arabiese gom bedek was op 20 d rakleeftyd was gelykstaande aan kontrole pruime van ‘n 5-10 d rakleeftyd. Na aanleidng van die bevinding, kan eetbare bedekkings dus die rakleeftyd van pruime verleng. ‘n Ontleding van die aromatiese vlugtige stowwe het bevestig dat die bedekkings nie ongewensde af geure in die pruime gevorm het nie.

'n Kommersiële proef was gedoen om te bevestig dat die toepassing van eetbare bedekkings vir die vrugtebedryf lewensvatbaar is. Bedekking formulering was geoptimaliseer deur verskillende variasies van arabiese gom (GA) te ondersoek, insluitend GA 2%, GA 5%, GA 10%, GA 5% + granaatsaadolie en GA 5% + askorbiensuur. Bedekkings was op 'African Delight™' pruime in 'n kommersiële pakhuis met 'n verstuiwer toegepas. Kommersiële paklyne is oor die algemeen toegerus om na-oesoplossings soos swamdoders aan te wend. Die toepassing van bedekkings op vrugte is dus

lewensvatbaar en ekstra infrastruktuur onkostes is nie noodsaaklik vir die implimentering daarvan nie. Vrugte was onderworpe aan regte lewe na-oes hantering tegnieke, en vrugkwaliteit was tydensdeur ‘n gesimuleerde versendingstydperk (-0.5 ± 2°C en 90 ± 5% RH vir ses weke) en daaropvolgende rakleeftyd (20 ± 2°C en 80 ± 5% RH vir 15 dae) getoets. GA 10% het die beste uit al die bedekkings presteer. Die bedekking het gelei tot 'n beduidende vertraging in fisiese-chemiese veranderinge tydens opberging, soos ‘n afname in fermheid, ‘n verlies in suurheid en ‘n verdonkering van skilkleur. Hierdie veranderinge was vertraag as gevolg van ‘n laer respirasie tempo en etileenproduksie wat gevolglik die tempo van vrugte-rypwording verlaag het. Pruime met ‘n GA 10% bedekking was deur 'n opgeleide sensoriese paneel tydens beskrywende sensoriese analise beskryf as onryp tot semi-ryp, terwyl kontrole pruime beskryf was as ryp tot oorryp. Dit stel voor dat die GA 10% bedekking wel die rakleeftyd van ‘African Delight™’ pruime kan verleng vir langer as die reedsbestaande eindpunt van vyf dae rakleeftyd van kommersiële pruime. Instrumentale metings het hierdie waarneming bevestig. Pruime wat met GA 10% bedek was het na 15 d rakleeftyd hulle fermheid (14.04 N), skilkleur (L* = 34.67 and *h*° = 6.37) en TOS (15.60 °Brix) gehandhaaf. Geen af geure was in die beskrywende sensoriese analise opgespoor nie. Pruime met GA 10% bedekking was ook mikrobies veilig teen 5 d rakleeftyd, met geen fekale koliforme nie en met die totale koliforme binne gespesifiseerde perke. Eetbare bedekkings het ook potensiaal vertoon as 'n groen vervangingstegnologie vir HDPE sakke. Geen beduidende verskil ($p \geq 0.05$) in respirasie tempo was waargeneem tussen bedekte pruime wat sonder HDPE sakke verpak was en kontrole pruime wat met HDPE sakke verpak was aan die einde van die koelopbergingsperiod nie. Die eetbare bedekkings kon dus 'n soortgelyke atmosfeer rondom pruime geskep het in vergelyking met die HDPE sakke wat uiteindelik gelei het tot vergelykbare fisiese-chemiese veranderinge tydens koelopberging. Alhoewel die kommersiële lewensvatbaarheid en tegnologiese gereedheid van GA 10% as 'n eetbare bedekking beperk is in hierdie studie, is die gebruik van arabiese gom as ‘n na oes eetbare bedekking baie belowend.

COMMUNICATIONS FROM THIS THESIS

Conference presentations

Riva, S.C., Opara, U.L. & Fawole, O.A. (2019). Effects of edible coatings on storage life and quality attributes of plums (oral). Presented at the Combined Congress 2019. Bloemfontein, South Africa, January 21-24, 2019.

Riva, S.C., Opara, U.L. & Fawole, O.A. (2019). Edible coatings as a green postharvest solution to extend storage life and maintain quality of plum fruit during simulated export condition (oral). Presented at the 2nd All Africa Postharvest Congress and Exhibition, Addis Ababa, Ethiopia, September 17 – 20, 2019.

Manuscripts in preparation

'Recent developments on postharvest application of edible coatings on stone fruit: a review.' – submitted to *Scientia Horticulturae*.

'Investigating the ability of edible coatings to prolong shelf life and alleviate shrivel in exported plums ('African Delight™').' – submitted to *Food Bioscience*.

'Evaluating the postharvest application of gum arabic-based edible coatings on shelf life and quality maintenance in exported plums: assessing commercial viability.' – submitted to *Scientia Horticulturae*.

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NOTE

This thesis is presented in the format prescribed by the Department of Food Science at Stellenbosch University. The structure is in the form of one or more research chapters (papers prepared for publication) and is prefaced by an introduction chapter with the study objectives, followed by a literature review chapter and culminating in a chapter for elaborating a general discussion, recommendations and conclusions. Language, style and referencing format used are in accordance with the requirements of the International Journal of Food Science and Technology. This thesis represents a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters has therefore been unavoidable.

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CHAPTER 1: GENERAL INTRODUCTION

1. Background

The Japanese plum (*Prunus salicina* Lindl.) is one of the most popular stone fruits consumed worldwide, characterised by its distinctive taste and high nutritional value (Wang *et al.*, 2018). Plums are harvested in the summer months; therefore, countries are forced to import fruit during their off-seasons to maintain a constant supply. After Chile, South Africa is the second biggest exporter of plums in the southern hemisphere, with 48% of fruit exported to the European Union (HORTGRO, 2018). Fruit can spend up to six weeks in shipment before reaching the export market. This long handling chain often results in significant quality losses that limit the economic value of plum exports.

With the exception of a few cultivars such as 'Sweet Miriam', plums are classified as climacteric fruit (Xin *et al.*, 2017; Farcuh, *et al.*, 2018). At the onset of ripening, plums produce ethylene that triggers several biochemical and enzymatic reactions which alter the physico-chemical properties of the fruit (Farcuh *et al.*, 2018). Oxygen serves as a crucial substrate for these reactions; therefore, the fruit's respiration rate increases during ripening (Ayranci & Tunc, 2004). In addition, plums experience high rates of moisture loss during postharvest storage as a consequence of the water vapour pressure deficit that exists between fruit and the surrounding environment (Kritzinger *et al.*, 2018). These physiological responses make plums a highly perishable commodity that is predisposed to postharvest loss.

Postharvest technologies are heavily relied on to maximise the profitability of exported plums. During shipment, fruit is held at low storage temperatures (-0.5°C) to suppress the ripening process and minimise physico-chemical changes (Valero *et al.*, 2013; Kritzinger *et al.*, 2018). Additionally, exported plums are packed with high density polyethylene (HDPE) bags to modify the atmosphere within the carton by increasing relative humidity and CO_2 levels in an attempt to reduce respiration and transpiration rates (Pesis *et al.*, 2000; Kritzinger *et al.*, 2018). However, postharvest losses in exported plums are still unfavourably high even with these technologies in place. In the 2018/2019 season, 18% of plums were rejected upon arrival at the export market due to quality-related issues (P. Roussouw 2019, personal communication, 26 July). Thus, there is a need for additional or alternative postharvest technologies to control quality losses in plums.

Recently, a lot of research has been done on edible coatings for postharvest fruit application. Edible coatings reduce the rate of ripening and control transpiration by forming a semi-permeable barrier around the surface of the fruit that regulates moisture loss and gaseous exchange between the fruit and the surrounding environment (Ncama *et al.*, 2018). Coatings have been widely reported as

a viable tool to maintain quality in many different types of fruit, such as banana (Maqbool *et al.*, 2011), sweet cherries (Martínez-Romero *et al.*, 2006; Mahfoudhi & Hamdi, 2015; Dong & Wang, 2018), guava (Hong *et al.*, 2012), table grapes (Meng *et al.*, 2008), mango (Baldwin *et al.*, 1999), strawberries (Gol *et al.*, 2013) and plums (Valero *et al.*, 2013; Kumar *et al.*, 2017; Thakur *et al.*, 2018). Coatings are comprised of food-grade materials and can be consumed with the fruit. The functionality of edible coatings is similar to that of the plum's natural waxy cuticle (Lara *et al.*, 2014), however, coatings are considerably more durable. During postharvest handling and washing procedures that take place in the orchard and the packhouse, the integrity of the fruit's cuticle is easily compromised (Maqbool *et al.*, 2011; Thakur *et al.*, 2018).

Polysaccharides are the most widely studied coating material as a result of their well-ordered and tightly packed hydrogen-bonded network structure (Tavassoli-Kafrani *et al.*, 2016; Arnon-Rips & Poverenov, 2018). This structural network offers excellent gas barrier properties and great mechanical properties to coatings. Furthermore, polysaccharides are highly available, allergen-free and typically soluble in water, making them suitable coating materials.

In addition to controlling physico-chemical changes, edible coatings may have the potential to control physiological disorders in plums such as shrivel (Certel *et al.*, 2004; Chaple *et al.*, 2017). Shrivel development affects many plum cultivars, impacting the visual appearance of the fruit and therefore, the consumer acceptability. Prolonged periods of cold storage have been reported to accelerate shrivel, with symptoms developing more rapidly and at a lower weight loss (Burdon *et al.*, 2014). Hence, shrivel control in exported plums is a major challenge. Several factors have been reported to influence shrivel development in plums. These include moisture loss (Kritzinger *et al.*, 2018), peel permeability (Kritzinger & Lötze, 2019) and textural losses (Ali *et al.*, 2010; Burdon *et al.*, 2014). Edible coatings have the ability to control these factors; therefore, the potential of coatings to control shrivel development in plums is promising.

Postharvest mechanical injury, weight loss and overripeness have been found to result in high decay incidence in exported fruit (Amorim *et al.*, 2008; Bal, 2013). Coating functionality can be easily enhanced through the incorporation of active ingredients such as antimicrobial and antioxidant agents to control decay in exported plums. Several authors have reported coatings to reduce postharvest decay by controlling the growth of various spoilage microorganisms such as *Penicillium expansum*, *Botrytis cinerea*, *Monilinia fructicola* and *Rhizopus stolonifer* (Li & Yu, 2001; Choi *et al.*, 2016; Andrade *et al.*, 2017). Coatings have also been reported to reduce the growth of pathogens such as *Salmonella Typhimurium* and *Escherichia coli* O157:H7 (Kim *et al.*, 2013). Hence, edible coatings may have the potential to replace synthetic fungicides commonly used on plums (Andrade *et al.*, 2017; Hajji *et al.*, 2018). The use of these fungicides is generally seen as undesirable by health

conscious consumers; therefore, coatings may provide a more natural approach to the control of postharvest decay.

Another prospect of edible coating application is the elimination of high density polyethylene (HDPE) bags used to pack exported plums (Vázquez-Celestino *et al.*, 2016). These single-use bags are both costly and unsustainable; hence, there is an urgent need for a green replacement technology. Coatings have been reported to create a similar modified atmosphere within the individual fruit to that created within the carton by the HDPE bags (Yaman & Bayoindirli, 2002).

2. Aim and objectives

2.1. Aim

Investigate the potential of edible coatings to improve the export quality of plums by reducing postharvest quality losses such as overripeness, shrivel and decay, and extending shelf life.

2.2. Objectives

The specific objectives of this study were to:

a) Select and screen edible coatings for postharvest application on plums
b) Optimise coating formulation using the candidate edible coating identified in objective (a)
c) Verify the real-life potential and feasibility of coating application in a commercial-scale trial.

3. Thesis structure

Literature review: provides a brief background of edible coatings and discusses the potential of coatings to extend the shelf life of stone fruit by reducing postharvest quality losses, with focus on coating formulation, properties and mode of action specific to stone fruit.

Research paper 1: focuses on screening of different edible coatings for their ability to prolong shelf life and alleviate shrivel in exported plums.

Research paper 2: optimises coating formulation for commercial application, by applying several gum arabic-based composite coatings to plums in a working packhouse, and assessing their effect on plum postharvest quality.

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CHAPTER 2: LITERATURE REVIEW

Recent developments on postharvest application of edible coatings on stone fruit: a review

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Abstract

Stone fruit are extremely popular worldwide as a result of their high nutritional value and desirable taste. However, the perishable nature of stone fruit makes them highly susceptible to postharvest losses such as weight loss, shrivel, decay and overripeness. Edible coatings have been widely reported to maintain the postharvest quality of stone fruit by reducing ripening, minimising decay and controlling the development of physiological disorders. Coatings function by forming a semi-permeable barrier on the surface of the fruit that controls moisture loss and gaseous exchange. There has been a lot of research on coating application for stone fruit whereby many different coating materials have been investigated. This review explores the potential of edible coatings to extend the shelf life of stone fruit by reducing postharvest quality losses, with focus on coating formulation, properties and mode of action specific to stone fruit. Furthermore, gaps in literature and future prospects of edible coating application on stone fruit are identified in this review.

Keywords: edible coating, postharvest, quality, stone fruit

1. Introduction

Stone fruit, including peaches, nectarines, plums, apricots and cherries, belong to the *Prunus* species (Wills *et al.*, 1983). They are referred to as drupes as a result of their morphology, consisting of a thin outer epicarp, edible fleshy mesocarp and a hard lignified stone (endocarp) in the centre of the fruit that encases the seed (Kader & Mitchell, 1989).

Due to their high nutritional value and desirable taste, the global demand for stone fruit is high. The major exporters of stone fruit are South Africa and Chile in the southern hemisphere, and Spain and Turkey in the northern hemisphere (HORTGRO, 2018). Exported fruit are subjected to a very long handling chain, often resulting in quality losses such as shrivel, decay, weight loss and overripeness. The stone fruit industry relies heavily on postharvest technologies as a means of maximising the economic potential of their harvests. These technologies act to reduce the rate of ripening and may include modified atmosphere packaging, low temperature storage, active and intelligent packaging, and treatment with chemical agents such as nitric oxide, chlorine dioxide, salicylic acid and 1-methyl cyclopropane (Choi *et al.*, 2016; Kumar *et al.*, 2017). Although these

technologies have shown to be effective in extending the shelf life of stone fruit, there are still some disadvantages to their application (Thakur *et al.*, 2018). Packaging of stone fruit typically includes large quantities of single-use, non-biodegradable materials such as plastic bags and liners (Tavassoli-Kafrani *et al*., 2016). The use of chemical agents on fruit is seen as undesirable, with consumers seeking safer and healthier foods with fewer additives and synthetic agents (Arnon-Rips & Poverenov, 2018). Cold storage has also been reported to lead to the development of chilling injury symptoms such as wooliness, flesh translucency, flesh bleeding and internal breakdown (Valero *et al.*, 2013; Kumar *et al.*, 2017). Furthermore, shrivel development in many stone fruit cultivars remains a postharvest challenge, despite the use of packaging solutions like high density polyethylene (HDPE) shrivel bags (Kritzinger *et al.*, 2018).

The application of edible coatings as a postharvest technology has been reported to reduce quality losses in cherries (Martínez-Romero *et al.*, 2006; Mahfoudhi & Hamdi, 2015; Dong & Wang, 2018), plums (Valero *et al.*, 2013; Kumar *et al.*, 2017; Thakur *et al.*, 2018), peaches (Maftoonazad *et al.*, 2008; Guillén *et al.*, 2013), apricots (Ghasemnezhad *et al.*, 2010; Zhang *et al.*, 2018) and nectarines (Ahmed *et al.*, 2009). Coatings impart a more durable protective barrier onto the epicarp of the fruit, compared to the fruit's natural waxy cuticle which is easily removed during postharvest washing and handling practices (Maqbool *et al.*, 2011; Thakur *et al.*, 2018). Authors widely report coating application to reduce the rate of ripening and extend the shelf life of stone fruit when used in combination with other postharvest technologies. However, coatings may have the potential to eliminate the need for costly and unsustainable packaging materials such as HDPE shrivel bags by providing a similar modified atmosphere effect (Yaman & Bayoindirli, 2002; Vázquez-Celestino *et al*., 2016). Edible coatings could also provide a more natural alternative to postharvest chemical treatments and synthetic fungicides (Andrade *et al*., 2017; Hajji *et al*., 2018). Furthermore, the aesthetic appearance of fruit could be improved through edible coating application, with coatings imparting an attractive shine, hiding minor scars and potentially even suppressing the development of physiological disorders such as shrivel by controlling moisture loss (Certel *et al*., 2004; Vázquez-Celestino *et al*., 2016; Chaple *et al*., 2017).

There are an extensive number of reviews available focusing on the general application of edible coatings to fresh produce (Lin & Zhao, 2007; Falguera *et al.*, 2011; Tavassoli-Kafrani *et al.*, 2016; Hassan *et al.*, 2018; Ncama *et al.*, 2018). To our knowledge, however, no review has been done on the application of edible coatings to stone fruit specifically. This paper focuses on postharvest application of edible coatings for stone fruit, with emphasis on quality maintenance, extension of storage life and control of physiological disorders and decay. Coating formulation, properties and mode of action are reviewed. Future prospects of edible coating application on stone fruit are also identified.

2. Postharvest losses of stone fruit

Stone fruit are climacteric, with the exception of cherries and some plum cultivars such as 'Sweet Miriam' (Xin *et al*., 2017; Farcuh, *et al.*, 2018). Climacteric fruit experience a burst of ethylene biosynthesis during ripening that triggers several biochemical and enzymatic reactions within the fruit (Minas *et al*., 2015; Farcuh *et al*., 2018). These reactions generally require oxygen as substrates; therefore, the respiration rate of the fruit increases with an increase in ethylene production (Guillén *et al*., 2013). Several physico-chemical changes occur as a result of an increase in respiration and ethylene production during ripening. Changes related to stone fruit ripening include fruit softening, colour changes, loss of acidity and increases in TSS (Valero *et al*., 2013; Kumar *et al*., 2017). Although these changes improve the eating quality of stone fruit, they also limit the shelf life and thus, the economic value of stone fruit.

Cherries have been classified as non-climacteric stone fruit (Alonso & Alique, 2004; Qayyum *et al.*, 2014), however, Ren *et al*. (2011) observed exogenous abscisic acid to stimulate ethylene production in cherries, indicating that cherries could have the potential to synthesize ethylene. In a study by Mahfoudhi and Hamdi (2015), cherries were reported to produce ethylene, with production increasing throughout storage as fruit ripened. Paul *et al.* (2012) reported the fading distinctions between classic ripening patterns in climacteric and non-climacteric fruit, suggesting the classification to potentially be oversimplified. Information regarding ethylene metabolism in cherries is scarce (Giné-Bordonaba *et al*., 2017); therefore, physico-chemical quality losses in cherries may occur through similar ripening pathways as other climacteric stone fruit.

In addition to physico-chemical changes, physiological disorders may cause significant postharvest quality losses in stone fruit. Major physiological disorders affecting stone fruit include shrivel, chilling injury and decay, which result from high rates of moisture loss, adverse storage conditions and microbial spoilage, respectively (Xin *et al*., 2017).

3. Edible coatings - an overview

The concept of coating fruit dates back to the 12th century in China, where oranges and lemons were waxed to reduce moisture loss and improve aesthetic appearance (Andrade *et al*., 2012). However, it was not until 1922 when the commercial application of wax to reduce postharvest losses in fruits and vegetables began (Raghav *et al*., 2016). These waxes, however, have been labelled as harmful to consumers, thus creating a niche for a more natural, sustainable coating application (Ncama *et al*., 2018).

In the past two decades, a great amount of research has been done on edible coating application. Edible coatings are made of food grade materials; thus, they can be safely consumed as part of the product (Tavassoli-Kafrani *et al*., 2016). Coatings are applied to fruit in liquid form by

dipping, spraying, brushing or dripping (Andrade *et al*., 2013; Tavassoli-Kafrani *et al*., 2016). They function to reduce quality losses by creating a semi-permeable protective barrier around the surface of the fruit that regulates moisture, solute and gaseous exchange between the fruit's internal environment and the external atmosphere (Ncama *et al*., 2018). Coatings completely cover the epicarp of the fruit, filling cracks and pores and sealing stomata and lenticels, as shown in Fig. 1 (Thakur *et al.*, 2013; Kumar *et al.*, 2017). As a result, coatings may enhance postharvest shelf life by retarding ripening, delaying physico-chemical changes and preventing the development of physiological disorders (Kumar *et al*., 2017).

3.1. Properties of edible coatings for stone fruit application

When applying edible coatings to stone fruit, several coating properties should be considered. Most importantly, coatings should not degrade the overall quality or result in physiological disorders in stone fruit, but rather minimise postharvest quality losses and extend shelf life (Ncama *et al.*, 2018). Edible coatings should be safe for human consumption, with all coating materials Generally Regarded As Safe by the Food and Drug Administration, or authorised as food additives by the European Union (Ncama *et al.*, 2018; Pashova *et al.*, 2018). Furthermore, edible coating production should be sustainable and nontoxic, with all processes and equipment adhering to food processing standards (Tavassoli-Kafrani *et al.*, 2016).

The coated epicarp of stone fruit is consumed. It is thus important that edible coatings do not alter the sensory properties of stone fruit in any way (Lin & Zhao, 2007). Therefore, properties such as coating thickness, adhesion to the surface, transparency, plasticity, waxiness, taste and smell should be carefully considered during coating formulation. Additionally, coating application should control gaseous exchange but not inhibit fruit respiration completely. This could lead to the development of fermentative volatiles which would give fruit an undesirable off-flavour (Alonso & Alique, 2004; Parreidt *et al.*, 2018).

For edible coatings to compete as a potential postharvest technology, coatings materials should be low cost and highly available. Coatings should be easy to apply, with good adhesive properties and immediate uniform drying characteristics (Ncama *et al.*, 2018). Furthermore, coating functionality and structural integrity must be maintained over extended storage periods. Coatings should have good flexibility to adapt with morphological changes in the fruit cuticle such as fruit shrinkage, shrivelling or mechanical damage.

3.2. Types of edible coatings for postharvest treatment of stone fruit

Edible coatings are comprised of proteins, polysaccharides, lipids or a combination of these materials, forming a composite-based edible coating (Hassan *et al.*, 2018). Proteins (wheat gluten, gelatin, corn

zein, whey, soy) are reported to impart good mechanical properties and gas barrier properties; however, their use in edible coatings may be limited due to ethical or religious beliefs as well as allergenic risks (Arnon-Rips & Poverenov, 2018). Furthermore, proteins-based edible coatings are reported to be brittle and susceptible to cracking (Lin & Zhao, 2007). Lipids (fatty acids, acylglycerol or waxes) are hydrophobic in nature, creating coatings with great moisture barrier properties (Ncama *et al.*, 2018). However, the mechanical properties and gas barrier properties of lipid-based coatings have been reported as poor (Arnon-Rips & Poverenov, 2018). Polysaccharides (gums, starches, pectins, cellulose-derivatives) are well-favoured and widely reported throughout literature for use in edible coating applications for all types of stone fruit, with particular interest in alginate (Díaz-Mula *et al.*, 2012; Valero *et al.*, 2013; Chiabrando & Giacalone, 2015), *Aloe* (Ahmed *et al.*, 2009; Guillén *et al.*, 2013; Paladines *et al.*, 2014), chitosan (Ghasemnezhad *et al.*, 2010; Bal, 2013; Kumar *et al.*, 2017), gum arabic (Asghar *et al.*, 2014; Mahfoudhi & Hamdi, 2015; Andrade *et al.*, 2017) and methyl cellulose (Ayranci & Tunc, 2004; Maftoonazad *et al.*, 2008; Choi *et al.*, 2016). Polysaccharides are highly available, allergen-free and typically soluble in water, making them suitable coating materials. They also have excellent mechanical properties and gas barrier properties as a result of a well-ordered and tightly packed hydrogen-bonded network structure (Tavassoli-Kafrani *et al.*, 2016; Arnon-Rips & Poverenov, 2018).

Composite-based edible coatings combine multiple coating materials to create a coating with improved functionality as a result of several advantageous properties (Arnon-Rips & Poverenov, 2018). Lipids are often incorporated into polysaccharide-based edible coatings to increase hydrophobicity, in an attempt to reduce postharvest moisture loss. In a study by Martínez-Romero *et al.* (2017), weight loss was significantly reduced in plums coated with *Aloe* and rosehip oil (9.95%) compared to *Aloe* without rosehip oil (14.28%). Similar results were observed in plums coated with hydroxypropyl methylcellulose formulated with oregano and bergamot essential oil (Choi *et al.*, 2016), and with whey protein isolate formulated with flaxseed oil blended with beeswax (Reinoso *et al.*, 2008).

4. Active ingredients in edible coatings for stone fruit application: forms and functions

4.1. Plasticizers to improve coating flexibility

Coating plasticity is an important property for stone fruit application. As moisture loss occurs during postharvest storage, stone fruit are prone to shrinkage and shrivel development (Kritzinger *et al.*, 2018). Therefore, coatings should have good flexibility which will enable them to adapt with morphological changes in fruit cuticle during storage.

Polysaccharide and protein-based coatings typically have poor flexibility as a result of strong intermolecular forces along polymer chains (Lin & Zhao, 2007). Although these forces provide good

barrier properties to coatings, they also make coatings stiff and brittle. Consequently, blisters, flakes or cracks in the coating may form as stone fruit shrink and shrivel throughout storage (Fig. 2).

Plasticizers such as glycerol, sorbitol, sucrose, mannitol, acetylated monoglyceride, polyethylene glycol and xylitol are often added to coatings to increase flexibility and prevent coatings from blistering, flaking and cracking (Lin & Zhao, 2007; Falguera *et al*., 2011). Plasticizers draw additional water into coating matrices and weaken intermolecular forces along polymer chains (Navarro-Tarazaga *et al.*, 2008). Navarro-Tarazaga *et al.* (2008) investigated the effect of two different plasticizers (glycerol and mannitol) in a hydroxypropyl methylcellulose-beeswax composite edible coating. Glycerol was found to be more successful in weakening polymer interactions, producing a more flexible film. In comparison to mannitol, glycerol has a lower molecular mass and is also a more hygroscopic compound. These two properties facilitate the development of a more flexible film: a low molecular mass allows the compound to easily diffuse into the polymer matrix, and a hygroscopic character draws additional water into the coating matrix, enhancing coating plasticity (Navarro-Tarazaga *et al.*, 2008). According to the author, the plasticizing effect improved as the concentration of glycerol increased.

An important consideration when incorporating plasticizers into a coating matrix, however, is the effect on the permeability of the coating. When plasticizers decrease polymer interactions and increase intermolecular spacing, the water vapour and gas barrier properties of the coatings may also increase (Navarro-Tarazaga *et al.*, 2008). Therefore, the concentration of plasticizer used in a coating should be carefully considered.

4.2. Emulsifiers and surfactants to improve coating adhesion

There is large variation in the types of epicarp surfaces amongst stone fruit. For instance, peaches have a sinuous and pubescent epidermis, whereas the epicarps of plums and cherries are smooth and waxy (Guillén *et al.*, 2013). Therefore, the surface active properties of edible coatings may need to be adjusted for specific stone fruit applications. Furthermore, lipids in coatings may migrate to the surface of the coating during high humidity storage, creating voids in the matrix and causing the coating to shrink (Reinoso *et al.*, 2008). As a result, the coating may dislodge from the surface and form blisters, flakes or cracks (Fig. 2). In addition to reducing the visual quality of the fruit, such disorders also reduce the barrier properties and thus the functionality of the coating (Reinoso *et al.*, 2008).

The addition of emulsifiers and surfactants to edible coatings may aid in the adhesion of coatings to stone fruit surfaces. Surfactants increase coating wettability, and emulsifiers stabilize coating matrices, preventing lipid migration by reducing the surface tension of water-lipid interfaces (Reinoso *et al.*, 2008; Kim *et al.*, 2013). Emulsifiers (soy lecithin, stearic acid and Tweens) and

surfactants (Tweens) have been used in edible coatings for plums (Reinoso *et al.*, 2008; Bal, 2013) and nectarines (Ahmed *et al*., 2009). However, some polysaccharides possess emulsifying properties, thus eliminating the need for an added emulsifier in polysaccharide-based composite coatings. Gum arabic and almond gum have been reported to have good emulsifying properties, with gum arabic performing better at low lipid concentrations, and almond gum being slightly superior for lipid concentrations above 5% (Mahfoudhi *et al.*, 2014). Other polysaccharides classed as hydrocolloids also exhibit emulsifying properties, such as alginate (Parreidt *et al.*, 2018) and methyl cellulose (Tavassoli-Kafrani *et al.*, 2016).

4.3. Active ingredients to improve antimicrobial activity

The high water activity in stone fruit may facilitate the growth of spoilage organisms such as *Penicillium expansum*, *Botrytis cinerea*, *Monilinia fructicola* and *Rhizopus stolonifer*, or pathogens such as *Salmonella Typhimurium* and *Escherichia coli* O157:H7 (Li & Yu, 2001; Navarro *et al*., 2011; Kim *et al.*, 2013; Zhang *et al.*, 2016; Andrade *et al.*, 2017). Edible coatings have been reported to exhibit antimicrobial properties, with the potential to replace synthetic fungicides as postharvest treatments (Bal, 2013; Andrade *et al.*, 2017). The antimicrobial activity of a coating can easily be improved through the incorporation of antimicrobial agents such as nisin, natamycin, natural seed extracts and essential oils (Choi *et al.*, 2016; Andrade *et al.*, 2017; Hajji *et al.*, 2018).

The incorporation of essential oils into edible coatings is widely studied in the literature, with reports of reduced postharvest losses in plums (Kim *et al*., 2013; Choi *et al*., 2016; Andrade *et al*., 2017; Martínez-Romero *et al*., 2017) as well as peaches, nectarines and cherries (Paladines *et al*., 2014). In addition to providing hydrophobic properties, essential oils also possess strong antimicrobial activity. Choi *et al.* (2016) observed the incorporation of oregano and bergamot essential oil in a hydroxypropyl methylcellulose (HPMC)-based coating to significantly reduce the number of viable microbial cells in plums, compared to when HPMC was applied without essential oils. A similar effect was observed by Andrade *et al.* (2017) where the incorporation of oregano and rosemary essential oils into gum arabic reduced the occurrence of soft rot in coated plums, compared to when plums were coated with gum arabic alone. Moreover, *E. coli* cell counts in plums were observed to decrease proportionally with increasing lemongrass oil concentrations in a carnauba wax-based coating (Kim *et al*., 2013).

4.4. Antioxidants to improve coating storability and functionality

Antioxidants such as ascorbic acid, citric acid and α-tocopherol may be added to coating matrices to prevent oxidative rancidity, degradation and discolouration (Lin & Zhao, 2007). The incorporation of antioxidants is popular in coatings for fresh cut produce, as discolouration is often a major

challenge. However, their use in coatings for whole stone fruit may also be beneficial. Antioxidant addition may prevent oxidative rancidity in coatings with high lipid concentration, prolonging the coating's shelf life (Tavassoli-Kafrani *et al.*, 2016). Furthermore, the addition of antioxidants to edible coatings could improve coating functionality. In a study by Liu *et al.* (2014), plums coated with chitosan-ascorbic acid exhibited reduced weight loss, fruit softening, acidity losses, colour changes, and oxidative stress throughout storage compared to plums coated with chitosan alone.

5. Effect of edible coatings on physiological responses of stone fruit

5.1. Respiration rate

Stone fruit continue to respire after harvest, absorbing oxygen for use in metabolic activities and releasing carbon dioxide and water as by-products (Ncama *et al.*, 2018). In climacteric stone fruit, respiration rate increases throughout ripening and typically peaks at the point whereby senescence is initiated, known as the climacteric peak (Maftoonazad *et al.*, 2008; Kumar *et al.*, 2017).

In 'Alberta' peaches coated with sodium alginate and methyl cellulose and stored at 15°C and 40% RH, respiration was reduced by 68% and 62%, respectively, and the climacteric peak was eliminated in coated fruit (Maftoonazad *et al.*, 2008). The author observed reduced physico-chemical losses in coated fruit as a result of suppressed respiration and thus a reduced ripening rate (Table 1) and reported shelf life to be extended from 15 days (control) to 21 days (sodium alginate) and 24 days (methyl cellulose). Similar results are widely reported throughout literature (Table 1). The gas barrier properties of edible coatings suppress respiration by limiting the amount of oxygen that can be absorbed by the fruit (Martínez-Romero *et al.*, 2017). However, oxygen levels within the fruit should be maintained above 3% to prevent anaerobic respiration and the development of off-flavours (Mahfoudhi & Hamdi, 2015).

Storage temperature has a major influence on the rate of respiration of fruit. Crisosto *et al.* (1993) observed respiration rate to increase proportionally with temperature in four cherry cultivars ('Bing', 'Brooks', 'Tulare' and 'King') stored at 0, 5, 10 and 20°C, taking into consideration that fruit could be exposed to a wide range of temperatures along the supply chain. Although authors have reported the oxygen permeability of various coatings at a single temperature and relative humidity (Baldwin *et al.*, 1999; Ribeiro *et al.*, 2007; Reinoso *et al.*, 2008), no study has investigated the effect of changing temperatures and thus changing respiration rates on coating gas barrier properties.

5.2. Ethylene production

Ethylene is a key hormone in the ripening process of climacteric stone fruit that enhances the activity of various enzymes responsible for postharvest changes (Valero *et al.*, 2013; Farcuh *et al.*, 2018). Ethylene production is controlled by 1-aminocyclopropane-1-carboxylic acid (ACC) synthase and

oxidase, known as the ripening enzymes (Thakur *et al.*, 2018). Oxygen serves as a crucial substrate for the activity of ripening enzymes, therefore, ethylene production is generally reduced in coated fruit as a consequence of suppressed respiration (Ayranci & Tunc, 2004; Valero *et al.*, 2013). In four plum cultivars ('Blackamber', 'Larry Ann', 'Golden Globe' and 'Songold') coated with alginate, ethylene production was significantly reduced at shelf life conditions (20°C and 65%) compared to control plums, resulting in reduced ripening, delayed postharvest losses (Table 1) and hence an extended shelf life (Valero *et al*., 2013). A similar effect was observed in peaches and plums coated with *Aloe* and stored at 20°C, 85% RH for six days (Guillén *et al*., 2013).

6. Effect of edible coatings on physico-chemical qualities of stone fruit

6.1. Firmness

Fruit firmness is one of the major factors governing consumer acceptance of stone fruit (Zhang *et al.*, 2018). As fruit ripen, cell wall degrading enzymes such as β-galactosidase, polygalacturonase and pectin methylesterase reduce cell-to-cell adhesion and cell wall mechanical strength, resulting in a loss of firmness (Maftoonazad *et al.*, 2008). These enzymes require oxygen to function and their activity is enhanced by ethylene production in climacteric fruit (Valero *et al.*, 2013).

Edible coatings have been reported to maintain firmness in nectarines (Ahmed *et al*., 2009), cherries (Mahfoudhi & Hamdi, 2015), peaches (Maftoonazad *et al*., 2008), plums (Navarro-Tarazaga *et al.*, 2008; Valero *et al.*, 2013) and apricots (Zhang *et al.*, 2018) by reducing respiration rate and ethylene production, which consequently reduces the activity of cell wall degrading enzymes. Kumar *et al.* (2017) reported a 78% reduction in fruit softening at the end of storage (1 ± 1°C, 90 ± 5% RH, 35 days) in plums coated with chitosan compared to control plums. The authors attributed the retention of firmness to a 44% reduction in pectin methylesterase activity in coated plums. Furthermore, a significant retention of firmness throughout storage (15°C and 40% RH) was observed in peaches coated with sodium alginate and methyl cellulose compared to the control (Maftoonazad *et al*., 2008). According to the authors, the observed reduced rate of fruit softening was attributed to a delay in fruit ripening, which corresponded to the overall maintenance of peach quality throughout the storage period (Table 1).

6.2. Pigments and colour attributes

Depending on the type of stone fruit, visible colour changes may occur during ripening. Certain plum cultivars, for example, are a light red-yellow colour when harvested, and develop a deep red-purple shade once ripe (Minas *et al*., 2015). Similarly, the red colour intensity in sweet cherry is used as an indicator of quality and ripening (Díaz-Mula *et al.*, 2012).

Colour changes in stone fruit occur as a result of anthocyanin and carotenoid synthesis during maturation and ripening (Valero *et al.*, 2013). Edible coatings have been reported to reduce colour changes in cherries (Martínez-Romero *et al.*, 2006; Chiabrando & Giacalone, 2015; Mahfoudhi & Hamdi, 2015), peaches (Guillén *et al.*, 2013; Hazrati *et al.*, 2017) and plums (Valero *et al.*, 2013; Kumar *et al.*, 2017; Thakur *et al.*, 2018). Coatings suppress respiration, thus limiting oxygen availability within the fruit, which consequently reduces the activity of phenylalanine ammonia-lyase and flavanone synthase, two key enzymes in anthocyanin synthesis (Tucker, 1993; Kumar *et al.*, 2017), and phytoene synthase/desaturase and f-carotene desaturase, enzymes catalysing carotenoid synthesis (Marty *et al.*, 2005; Valero *et al.*, 2013). Kumar *et al.* (2017) found chitosan-coated 'Santa Rosa' plums to have a 24% delay in the rate of anthocyanin development in comparison to uncoated plum samples at the end of storage (1 ± 1°C, 90 ± 5% RH, 35 days), which correlated with a reduction in chroma index (28%) and hue angle (51%) in coated fruit.

6.3. Total soluble solids and titratable acidity

Total soluble solids (TSS) is one of the most important factors determining the eating quality of stone fruit. TSS gives an indication of fruit sweetness and it is known to increase during ripening as starch is hydrolysed into simple sugars by catabolic processes such as respiration (Mahfoudhi & Hamdi, 2015). Postharvest moisture loss may also contribute to increases in TSS, increasing the concentration of sugars within the fruit, however, starch breakdown often has a greater influence on changes in TSS (Andrade *et al.*, 2017).

Edible coatings have been reported to reduce increases in TSS content during storage as a result of suppressed respiration (Liu *et al.*, 2014; Mahfoudhi & Hamdi, 2015; Andrade *et al.*, 2017). Coatings decrease fruit metabolism, consequently delaying the breakdown of starch and resulting in maintenance of TSS throughout storage. Mahfoudhi and Hamdi (2015) reported a gradual increase in TSS for both coated and uncoated cherries throughout storage (2°C, 90–95% RH for 16 days). At the end of the storage period, however, TSS was significantly higher in control fruit (25%) compared to fruit coated with gum arabic and almond gum, having 18.1% and 19% increases in TSS, respectively. Coating application was reported to reduce ripening and delay the breakdown of starches, in addition to delaying other physico-chemical changes (Table 1). Similar results were reported by Ahmed *et al.* (2009) in *Aloe*-coated nectarines stored at 0 ± 0.5°C and 90 ± 5% RH for six weeks followed by 20 ± 1°C and 60 ± 5% RH for eight days.

Titratable acidity (TA) is another important factor involved in the eating quality of fruit. TA gives an approximation of the total acidity of a solution and is often decreased throughout postharvest storage as organic acids are used as primary substrates for respiration and other metabolic processes

(Mahfoudhi & Hamdi, 2015). In stone fruit, malic acid is the major organic acid used in such processes (Tucker, 1993).

Edible coatings have been reported to minimise TA losses in nectarines (Ahmed *et al*., 2009), cherries (Díaz-Mula *et al*., 2012), peaches (Maftoonazad *et al*., 2008), plums (Valero *et al*., 2013) and apricots (Zhang *et al.*, 2018) throughout storage. Coatings barrier properties limit the amount of oxygen absorbed by the fruit, consequently reducing respiration and thus decreasing the use of organic acids (Hazrati *et al.*, 2017). According to Kumar *et al.* (2017), TA in uncoated 'Santa Rosa' plums decreased during storage (1°C and 90 ± 5% RH for 35 days), however, the decline in TA was reduced by 32% in plums coated with chitosan. Similarly, Ahmed *et al*. (2009) reported that nectarines coated with *Aloe* had a significantly higher TA (29%) than control fruit at the end of storage (0 ± 0.5°C, 90 ± 5% RH for six weeks followed by 20 ± 1°C, 60 ± 5% RH for eight days).

7. Effect of edible coatings on phytochemical and antioxidant contents of stone fruit

Stone fruit are widely reported to be rich in phenolic compounds, making them highly nutritious (Liu *et al*., 2015; Wang *et al.*, 2018; Zhao *et al*., 2018). Phenolic compounds are secondary metabolites produced in plants during maturation and ripening (Amiot *et al.*, 1997). Flavonoids are a major subgroup of polyphenols, including anthocyanins, flavones, anthoxanthins and more (Silva & Sirasa, 2018). These compounds all possess strong antioxidant capacity, capturing free radicals produced during oxidative stress (Nair *et al*., 2018).

Total phenolic content and antioxidant capacity has been reported to increase significantly in both the peel and flesh of stone fruit during maturation and ripening, with concentrations being 4–5-fold higher in the peel than in the flesh (Díaz-Mula *et al.*, 2012; Kumar *et al.*, 2017; Martínez-Romero *et al.*, 2017). As fruit begin to senesce, however, there is a decrease in phenolic compounds due to cell structural breakdown (Gol *et al*., 2013; Thakur *et al*., 2018). Kim *et al*. (2013) reported the activities of phenol oxidase and peroxidase to reduce phenolic content, thus decreasing the nutritional value of stone fruit.

Edible coatings have been reported to reduce polyphenol losses and maintain higher antioxidant capacity throughout postharvest storage of cherries (Díaz-Mula *et al.*, 2012), plums (Kumar *et al.*, 2017; Thakur *et al.*, 2018) and apricots (Ghasemnezhad *et al.*, 2010). Coatings slow the rate of ripening, thus delaying the onset of senescence and reducing cell structural breakdown. Additionally, coatings reduce respiration, decreasing the amount of oxygen available within the fruit for metabolic activities and thus, reducing the activity of phenol oxidase and peroxidase (Maftoonazad *et al.*, 2008).

Díaz-Mula *et al.* (2012) observed a continuous increase in phenolic compounds in alginate-coated sweet cherries throughout a 16-day cold storage period (2°C, 90% RH), followed by two days

at shelf life conditions (20°C). This contrasted with uncoated fruit, which showed an initial increase in phenolic content, followed by a decline after eight days of storage at 2°C. Thus, the coating allowed an accumulation of phenolic compounds during storage without any decline.

In addition to phenolic compounds, ascorbic acid and carotenoids also possess antioxidant activity (Ahmed *et al.*, 2009). Ascorbic acid is able to scavenge the superoxide and hydroxyl radicals, as well as regenerate a-tocopherol (Ghasemnezhad *et al.*, 2010). In cherries coated with guar gum and ginseng extract stored at 20°C, 70-75% RH for eight days (Dong & Wang, 2018) and plums coated with chitosan stored at 1 ± 1°C, 90 ± 5% RH for 35 days (Kumar *et al*., 2017), ascorbic acid content was maintained compared to control fruit throughout storage. The authors attributed the observed effect to low oxygen availability within the fruit, resulting in reduced enzyme activity and oxidation of ascorbic acid. Edible coatings have been reported to reduce carotenoid synthesis in plums by reducing respiration and ethylene production, which consequently reduces the activity of enzymes catalysing carotenoid synthesis (Marty *et al.*, 2005). Valero *et al.* (2013) reported total carotenoids to increase in peel of four plum cultivars, two of which were purple-skinned plums ('Blackamber' and 'Larry Ann') and two of which were yellow-skinned cultivars ('Golden Globe' and 'Songold'), when fruit were stored at 2°C, 90% RH for 35 days, followed by 20°C, 65% RH for three days. The increase was delayed in all plum cultivars when fruit were coated with alginate.

8. Effect of edible coatings on physiological disorders and decay in stone fruit

8.1. Weight loss

From the moment fruit is harvested, it stops receiving water from the parent plant and immediately begins to lose moisture through transpiration (Díaz-Pérez *et al.*, 2007). Moisture loss accounts for 97% of the total weight loss in fruit, with weight loss due to respiration generally considered negligible (Díaz-Pérez *et al.*, 2007; Maftoonazad *et al.*, 2008). Besides a loss of saleable weight, moisture loss has also been linked to the occurrence of shrivel, associated with fruit softening and shown to have a parallel trend with decay rate (Bal, 2013; Xin *et al.*, 2017; Kritzinger *et al.*, 2018).

Edible coatings have been widely reported to significantly reduce weight loss in nectarines (Ahmed *et al*., 2009; Paladines *et al*., 2014), peaches (Maftoonazad *et al.*, 2008; Hazrati *et al.*, 2017), apricots (Sumnu & Bayindirli, 1995; Zhang *et al.*, 2018), plums (Valero *et al.*, 2013; Kumar *et al.*, 2017) and cherries (Martínez-Romero *et al*., 2006; Dong & Wang, 2018). Coatings cover the fruit's epicarp, filling cracks and pores and coating stomata and lenticels, making it difficult for fruit to transpire freely (Kumar *et al.*, 2017).

The addition of lipids to coatings increases coating hydrophobicity and has been reported have an enhanced effect on reducing moisture loss. In plums coated with *Aloe* formulated with rosehip oil, weight loss was further reduced compared to when plums were coated with *Aloe* alone (Martínez-

Romero *et al*., 2017). A similar effect was observed in plums coated with carnauba wax formulated with lemongrass oil (Kim *et al*., 2013), plums coated with gum arabic formulated with oregano and rosemary essential oil (Andrade *et al*., 2017) and plums coated with whey protein isolate formulated with flaxseed oil (Reinoso *et al*., 2008).

8.2. Shrivel

Shrivel is a common physiological disorder in stone fruit, rendering fruit unsaleable due to its undesirable appearance (Certel *et al*., 2004; Kritzinger *et al.*, 2018). There are many different factors that influence shrivel development in stone fruit; however, moisture loss is widely reported to have the greatest influence (Crisosto & Day, 2012; Vázquez-Celestino *et al.*, 2016; Kritzinger *et al.*, 2018). As fruit lose moisture, there is a loss of turgor in the epidermal cells, resulting in an overall reduction in fruit volume (Kritzinger *et al.*, 2018). Because the cuticle has limited elasticity and maintains its surface area, a shrivelled appearance results.

According to Crisosto and Day (2012), moisture loss of as low as 5% is sufficient in causing shrivel in peaches and nectarines, however, this limit may differ between stone fruit cultivars. Additionally, when fruit is cold stored for extended periods, shrivel development has been reported to occur more rapidly and at a lower weight loss (Burdon *et al.*, 2014).

Textural losses have also been associated with shrivel development in stone fruit. As fruit softens, pectin is hydrolysed by cell wall degrading enzymes, forming voids in the cellulose-hemicellulose network (Ali *et al.*, 2010; Burdon *et al.*, 2014). Free water fills these spaces, binding to cell wall components and reducing the overall water motility within the fruit tissue. Further moisture loss results in rapid shrivel development, due to a lack of mobile water within the fruit to maintain hydration just under the epicarp.

Lastly, peel permeability has been reported to influence the susceptibility of a cultivar to shrivel development. The relationship between peel permeability and the number of open lenticels on the surface of four different Japanese plum cultivars was investigated, however, no association was found between the two factors (Kritzinger & Lötze, 2019). A potential link between peel permeability and cuticle composition, however, has been suggested. Shrivel susceptibility was reported to be greater in plums with larger intercellular spaces and a more elastic, flexible cuticle as a result of a low phenol content, many tri-hydroxy acids, and a low primary alcohol content (Kritzinger *et al*., 2019).

Edible coatings may have the potential to control shrivel development in stone fruit. Certel *et al*. (2004) reported cherries coated with a sodium caseinate-milk protein coating to be free from shrivelling whilst uncoated cherries shrivelled after 20 days at 4°C, 80–85% RH. To our knowledge, this is the only study reporting on the ability of edible coatings to reduce shrivel in stone fruit.

However, there is an abundance of literature documenting the ability of edible coatings to reduce moisture loss in stone fruit, as well as textural losses and peel permeability (Maftoonazad *et al.*, 2008; Mahfoudhi & Hamdi, 2015; Kumar *et al.*, 2017; Dong & Wang, 2018; Thakur *et al.*, 2018). Therefore, the viability of edible coating application for shrivel control in stone fruit may be promising.

8.3. Chilling injuries

Chilling injuries in stone fruit can take on several different forms: internal browning, flesh translucency (also called gel breakdown), flesh reddening and dry, mealy, woolly or hard-textured flesh (Crisosto & Day, 2012; Valero *et al.*, 2013). Stone fruit cultivars vary in susceptibility to chilling injury symptoms, with peach cultivars reported to be more susceptible than nectarine cultivars, and some plum cultivars like 'Friar', 'Showtime' and 'Howard Sun' being highly disposed to developing chilling injury symptoms (Crisosto *et al.*, 1999).

Chilling injury symptoms tend to develop in fruit stored at temperatures between 2 and 7°C, rather than when fruit is stored at 0°C or below, but above freezing point (Crisosto & Day, 2012). Therefore, maintaining appropriate temperatures throughout the handling chain is crucial for the prevention of these postharvest disorders.

Information regarding the effect of edible coatings on chilling injury symptoms in stone fruit is scarce. Navarro-Tarazaga *et al.* (2008) reported flesh bleeding to be reduced in plums coated with a hydroxypropyl methylcellulose composite-coating compared to control plums when fruit was stored at 1°C, 85% RH for eight weeks. To our knowledge, however, there is no other record of the effect of edible coatings on chilling injury symptoms in stone fruit.

8.4. Decay

Microbial decay in stone fruit is typically due to *Penicillium expansum*, *Botrytis cinerea*, *Monilinia fructicola* and *Rhizopus stolonifer*, causing green/blue mould rot, grey mould rot, brown rot and soft rot respectively (Li & Yu, 2001; Navarro *et al.*, 2011; Zhang *et al.*, 2016; Andrade *et al.*, 2017), but has also been reported to occur as a result of *Salmonella Typhimurium* and *Escherichia coli* O157:H7 (Kim *et al.*, 2013).

Edible coatings have been widely reported to reduce microbial decay in stone fruit, with increased antimicrobial action when incorporating active ingredients (Andrade *et al.*, 2017; Dong & Wang, 2018; Ncama *et al.*, 2018). Guar gum was found to reduce decay in sweet cherries stored at 20°C, 70-75% RH for eight days, from 43% in the control, to 26% in coated fruit. When ginseng extract was incorporated into the coating, decay incidence was further reduced, with only 13% of fruit perishing (Dong & Wang, 2018). Chitosan, in particular, is widely reported as having natural antimicrobial properties (Ahmed *et al.*, 2009; Bal, 2013; Hajji *et al.*, 2018; Zhang *et al.*, 2018). In a

study by Bal (2013), decay incidence at the end of a 40 day cold storage period (0-1°C, 90 ± 5% RH) was reduced from 33.1% in uncoated 'Giant' plums to 5.7% in plums coated with chitosan.

Kim *et al*. (2013) demonstrated coating application to be effective in inhibiting cell growth in plums, both when plums were inoculated pre-coating as well as post-coating. Therefore, coatings may be effective in reducing microbial growth regardless of when infection occurred. When plums were inoculated pre-coating, however, the antimicrobial effect of the coating was slightly reduced. The author hypothesised that microbial cells may have been internalised into the plum's epicarp, reducing the contact between the coating and cells and thus, decreasing antimicrobial action.

9. Conclusions and future prospects

Edible coating application has huge potential in prolonging the shelf life of stone fruit, by delaying the ripening process and reducing quality losses. The use of polysaccharide-based edible coatings is widely reported throughout literature, thus their application to stone fruit is most promising. The addition of lipids to polysaccharide-based coatings has been shown to increase coating moisture barrier properties, reducing transpiration rates and enhancing postharvest storability. Furthermore, the incorporation of plasticizers, emulsifiers and surfactants, as well as antimicrobial agents and antioxidants, may create a coating with improved functionality. Stone fruit responded well to the application of edible coatings and thus, this technology may provide a sustainable, cost-effective and a natural postharvest approach to the postharvest management of stone fruit.

A lot of research has been done to investigate different types of edible coatings and optimise coating formulation for stone fruit. However, no study has considered the commercial viability of edible coating application to stone fruit or investigated the performance of edible coatings when applied in a real-life, commercial-scale trial. In a laboratory-scale trial, fruit are coated using a dipping-action, and conditions are carefully controlled. In commercial packhouses, however, fruit are subjected to postharvest handling practices and often endure temperature abuse. Pack lines are also generally equipped with atomizers which apply postharvest solutions using a spray-action. This is because atomizers can be easily automated for high volume production, use less solution per batch and prevent contamination of the coating. However, spraying has been reported to deposit less coating onto the product's surface compared to dipping, resulting in a thinner barrier (Zhong *et al*., 2014), or result in incomplete surface coverage (Lerdthanangkul & Krochta, 1996). Therefore, the response of fruit coated in laboratory-scale trials may differ significantly from that of fruit coated in commercial-scale trials, and thus, laboratory-scale trials cannot be used as an accurate representation when considering commercial viability.

In addition to commercial viability, there is a lack of information regarding the real-life impact and sustainability of edible coating application. Coatings are widely reported to create a modified

atmosphere effect within the fruit, similar to that created with HDPE bags used in packaging stone fruit. However, to our knowledge, no study has investigated the potential of edible coating application to replace the need for costly and unsustainable HDPE bags in the packaging of stone fruit.

Future research direction must focus on technological readiness level of edible coating application for postharvest applications in stone fruit. There is a need to consider the performance of edible coatings in a commercial set up, taking into consideration the performance of different application techniques and postharvest handling practices, as well as the sustainability and cost implications of edible coating as an alternative postharvest technology. This could provide a science based-tool to help in the adoption of edible coating technology in the stone fruit industry.

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Table 1. Studies on edible coating application to control physiological responses and maintain physico-chemical qualities in stone fruit

Edible coating	Formulation	Storage regime	Fruit application	Key Findings	Reference
Alginate	1, 3 or 5%	Fruit stored at 2°C, 90% RH for 16 days, followed by storage at 20°C for two days In a separate trial, fruit were stored at 20°C for two days	Sweet cherry ('Sweetheart')	Respiration reduced in coated fruit; no climacteric peak observed (control fruit peaked at 12 d) Fruit firmness, hue angle and TA significantly higher in coated fruit; increasing effect with increasing concentration (5% most effective) No significant difference in TSS between coated and control fruit	Díaz-Mula *et al.* (2012)
Alginate (A) or methyl cellulose (MC)	2% (A); 3% (MC)	Fruit stored at 15°C, 40% RH for 21 days (A) and 24 days (MC)	Peach ('Alberta')	Respiration significantly reduced in coated fruit, with MC (68%) having a greater effect than A (62%); no climacteric peak observed in coated fruit (control fruit peaked at 10 d) Firmness and TA significantly higher in coated fruit, with MC having a greater effect than A No significant difference in TSS between coated and control fruit	Maftoonazad *et al.* (2008)
Alginate	1% or 3%	Fruit stored at 2°C, 90% RH for 35 days, followed by storage at 20°C, 65% RH for three days	Plum ('Blackamber', 'Golden Globe', 'Larry Ann' and 'Songold')	Ethylene production signifcantly reduced in coated fruit, with 3% having the greatest effect Fruit firmness significantly higher in coated fruit, with 3% having the greatest effect Chroma significantly higher in coated fruit, with no significant difference between 1% and 3% (except golden globe) Acidity higher in coated plums ('Blackamber', 'Golden Globe', and 'Songold')	Valero *et al.* (2013)

Table 1 (Continued). Studies on edible coating application to control physiological responses and maintain physico-chemical qualities in stone fruit

Aloe with rosehip oil	*A. arborescens* (AA) or *A. vera* (AV) extract; with or without 2% rosehip oil (RO)	Fruit stored at 2°C, 90% RH for 28 days, followed by storage at 20°C, 85% RH for two days In a separate trial, fruit were stored at 20°C, 85% RH for 28 days	Plum ('President')	Respiration and ethylene production significantly reduced in coated fruit; AA+RO had the best effect TA significantly higher in coated fruit, with no significant difference between coatings Firmness significantly higher in coated fruit, with AA+RO having a significantly greater effect Hue significantly higher in coated fruit, with AA+RO and AV+RO having a greater effect TSS/TA significantly lower in coated fruit, with AA+RO and AV+RO having a greater effect	Martínez-Romero *et al*. (2017)
Chitosan	2%; 0.2% glacial acetic acid; 0.1% Tween 80	Fruit stored at 1±1°C, 90±5% RH for 35 days	Plum ('Santa Rosa')	Respiration and ethylene production reduced in coated fruit; climacteric peak suppressed and delayed from 14 days (control) to 28 days (coated) Firmness significantly higher in coated fruit Chroma/hue angle significantly higher in coated fruit TA significantly higher in coated fruit TSS significantly lower in coated fruit	Kumar *et al*. (2017)
Guar gum (GG) with ginseng extract (GSE)	0.15%; with or without 1% w/v GSE	Fruit stored at 20°C, 70-75% RH for eight days	Sweet cherry (cultivar not specified)	Respiration significantly reduced in coated fruit, with GG+GSE having a significantly greater effect Firmness significantly higher in coated fruit, with no significant difference between coatings TA was significantly higher in coated fruit, with GG+GSE having a significantly greater effect TSS was significantly lower in coated fruit, with GG+GSE having a significantly greater effect	Dong & Wang (2018)
Gum arabic or almond gum	10%	Fruit stored at 2°C, 90-95% RH for 15 days	Sweet cherry (cultivar not specified)	Ethylene production and respiration rate significantly reduced in coated fruit Firmness, TA, hue angle and SSC maintained in coated fruit, with no significant difference between coatings	Mahfoudhi & Hamdi (2015)

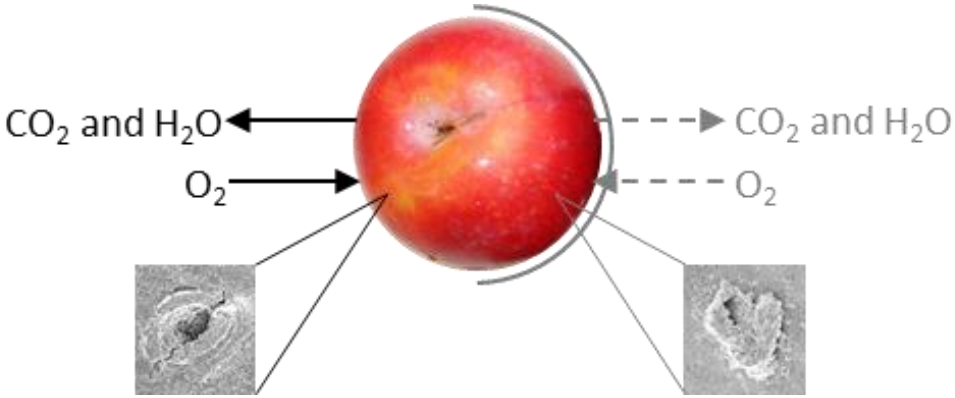

Figure 1. Schematic diagram of uncoated fruit (high respiration rate; open lenticel) versus coated (reduced respiration rate; lenticel completely covered by coating) fruit.

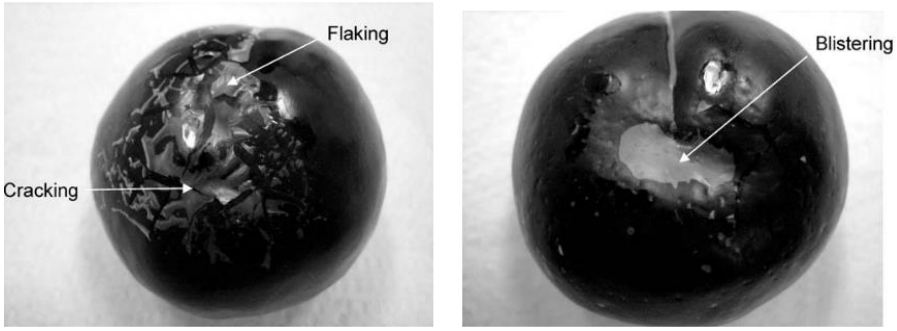

Figure 2. Defects observed in whey-protein coated plums after 15 days of storage at 5°C (Reinoso *et al.*, 2008).

CHAPTER 3: RESEARCH PAPER 1

Effectiveness of edible coatings to prolong shelf life and alleviate shrivel in exported plums ('African Delight™').

Abstract

Plums experience significant quality losses during the long chain of export and sale. The effect of six edible coatings, four of which were experimental (alginate, chitosan, gellan gum and gum arabic) and two commercial (High shine and Sta-fresh), was investigated on the postharvest quality of 'African Delight™' plums throughout a simulated shipping period (-0.5 ± 2°C and 90 ± 5% RH for five weeks) and a subsequent shelf life period (20 ± 2°C and 80 ± 5% RH for 20 days). Weight loss at 20 d shelf life was significantly ($p<0.05$) reduced in plums coated with gellan gum (1.93%), gum arabic (5.36%), High shine (0.60%) and Sta-fresh (2.38%) compared to control plums (23.62%). Similarly, shrivel incidence was significantly ($p<0.05$) lower in plums coated with gellan gum (5.46%), gum arabic (4.91%), High shine (4.61%) and Sta-fresh (7.02%) compared to control plums (9.56%) at 20 d shelf life. In addition, decay was significantly ($p<0.05$) reduced from 7.57% in control plums to between 0% and 1.26% in plums coated with alginate, gellan gum and gum arabic. Respiration rate and ethylene production were delayed in coated plums compared to control plums, resulting in reduced physico-chemical changes during cold storage and shelf life. Plums coated with alginate, chitosan and gum arabic at 20 d shelf life resembled control plums at 5-10 d shelf life, indicating an extension of shelf life. According to volatile analysis, none of the investigated coatings developed fermentative off-flavour volatiles such as acetaldehyde, methanol and 2-phenyl ethyl acetate. Amongst the investigated edible coatings, gum arabic had the best performance for exported plums, as it reduced shrivel incidence, maintained postharvest quality and extended shelf life.

Keywords: gum arabic, postharvest, quality, stone fruit

1. Introduction

The Japanese plum (*Prunus salicina* Lindl.) is one of the most popular stone fruits consumed worldwide, characterised by its distinctive taste and high nutritional value (Wang *et al.*, 2018). However, the economic value of plums is limited by a short shelf life due to their climacteric and highly perishable nature (Martínez-Romero *et al.*, 2003; Minas *et al.*, 2015). During export, plums are exposed to a long handling chain, with shipping periods lasting between four and six weeks. Postharvest technologies such as low temperature storage and high density polyethylene (HDPE) bags

are used to slow the rate of ripening and prevent moisture loss during shipment. However, even with these technologies in place, quality losses such as overripeness, decay, shrivel and weight loss remain high in exported plums (Kritzinger *et al.*, 2018a).

Edible coatings have been widely reported to reduce postharvest losses in many different types of fruit, including banana (Maqbool *et al.*, 2011), sweet cherries (Martínez-Romero *et al.*, 2006; Mahfoudhi & Hamdi, 2015; Dong & Wang, 2018), guava (Hong *et al.*, 2012), table grapes (Meng *et al.*, 2008), mango (Baldwin *et al.*, 1999), strawberries (Gol *et al.*, 2013) and plums (Valero *et al.*, 2013; Kumar *et al.*, 2017; Thakur *et al.*, 2018). Coatings form a semi-permeable barrier on the fruit surface that controls moisture loss and gaseous exchange, consequently reducing weight loss and delaying changes related to ripening such as fruit softening, colour changes, loss of organic acids and the breakdown of starches into sugars (Ncama *et al.*, 2018). Throughout literature, different types of edible coatings have been investigated; however, polysaccharide-based coatings are considered most favourable. Polysaccharides are readily available, allergen-free and usually soluble in water. Furthermore, they have excellent gas barrier properties and great mechanical properties as a result of their well-ordered and tightly packed hydrogen-bonded network structure (Tavassoli-Kafrani *et al.*, 2016; Arnon-Rips & Poverenov, 2018).

In addition to reducing physico-chemical quality losses, edible coatings may have the potential to reduce shrivel in plums. Shrivel is a major physiological disorder affecting many plum cultivars, such as 'African Delight™' (Kritzinger & Lötze, 2019). In 2018/2019, 8% of exported 'African Delight™' plums were reported shrivelled upon arrival at the export market, even with the use of HDPE bags and low temperature storage (P. Rossouw, personal communication, 26 July 2019). As plums lose moisture through transpiration, there is a loss of turgor in the epidermal cells, resulting in an overall reduction in fruit volume (Kritzinger *et al.*, 2018a). This results in a shrivelled appearance, because the plum's waxy cuticle has limited elasticity and maintains its surface area. Shrivel occurs as a result of two factors, namely peel permeability and moisture loss (Kritzinger *et al.*, 2018a). Coatings have the ability to control these two factors, by providing a protective barrier to high rates of respiration and transpiration (Kumar *et al.*, 2017). In 'Pusa Jwala' chillies coated with methyl cellulose (Chaple *et al.*, 2017) and 'Bing' cherries coated with a milk protein-based coating (Certel *et al.*, 2004), shrivel was reported to be reduced compared to the control.

To our knowledge, no study has explored the potential of edible coatings to reduce shrivel in plums. Therefore, the aim of this study was to evaluate the efficacy of two commercial coatings and four polysaccharide-based coatings, including alginate, chitosan, gellan gum and gum arabic, on reducing shrivel, maintaining quality attributes and prolonging shelf life of 'African Delight™' plums during simulated export and shelf life conditions.

2. Materials and methods

2.1. Fruit procurement and handling

Plum fruit ('African Delight™') were hand-picked at commercial harvest (mid-February 2018 in Paarl, Western Cape, South Africa, 33.7342°S, 18.9621 °E) and transported to the laboratory within 48 h of harvest using an air-conditioned vehicle. Upon arrival, homogenous in size and free of blemishes, cracks and bruises were washed with distilled water and wiped dry using a soft cloth to remove the natural waxy cuticle and ensure better coverage and adhesion of the edible coating to the fruit.

2.2. Edible coatings

Four polysaccharide-based experimental coatings; alginate, chitosan, gellan gum and gum arabic (Sigma Aldrich) and two commercial coatings; Sta-fresh (xantham gum-based, applied in local packhouses) and High shine (carnauba wax-based, applied internationally), were used for this experiment. Based on concentrations established in preliminary trials, the following formulations were prepared in the specific order and composition, using distilled water (60°C) to make up the various solutions;

1) Alginate (2% w/v) and vegetable oil (2% w/v) plus separate preparation of 2% calcium chloride solution as a supplementary dip to initiate cross linkage
2) Chitosan (1.5% w/v), Tween-20 (0.05% w/v) and acetic acid (0.5% w/v)
3) Gellan gum (0.5% w/v), vegetable oil (1% w/v), glycerol (1% w/v) and Tween-20 (0.1% w/v)
4) Gum arabic (2% w/v), vegetable oil (1% w/v) and glycerol (1% w/v)

All coating materials were obtained from Sigma Aldrich, except for vegetable oil which was obtained from a local grocer.

According to the products' application instructions, Sta-fresh (5) was used at 8.75% by diluting with distilled water, and High shine (6) was used in concentrated form.

2.3. Laboratory-scale coating application, storage and testing

Fruit were divided into seven lots of 350 fruit, with six lots each receiving a different coating treatment (1-6). Plums were immersed into the respective coating for 2 min, and then placed on racks to air dry at 30°C for 30 min. Plums were then packed into double-layer cartons (39x29x12cm) containing 50 fruit per carton with high density polyethylene (HDPE) bags according to industry practice. The seventh lot fruit was used as a control, whereby plums were washed with distilled water, wiped dry with a cloth and then packed.

All fruit were stored at -0.5 ± 2°C and 90 ± 5% relative humidity (RH) for five weeks, simulating shipping conditions, followed by a subsequent 20 day shelf life period at 20 ± 2°C and 80 ± 5% relative humidity (RH), where the cartons were opened and the HDPE bags were removed. This long shelf life period was extended past the commercial sale end point of shelf life (five days) in order to evaluate the shelf life extension potential of the edible coatings. Temperature and relative humidity were monitored throughout storage using a data logger (Tinytag TV-4500, Gemini Data Loggers, UK). Quality parameters were measured at harvest, at weekly intervals during cold storage and at five day intervals during the shelf life period using 20 randomly selected fruit per treatment for each sampling date.

2.4. Scanning electron microscopy

Scanning electron microscopy was used to visualise the microscopic differences in fruit surface morphology between coated plums, uncoated plums with the natural waxy cuticle intact, and uncoated plums with natural wax removed by a preliminary washing step.

Sample preparation and analysis followed the method described by Cronje *et al*. (2011). Plum samples (5 mm x 5 mm x 5 mm) were taken from the shoulder of the fruit (Fig. 1, Appendix), with the plum peel intact, and fixed in a 1:1 (v/v) solution of 2.5% glutaraldehyde and 2.5% formaldehyde in 0.075 M phosphate buffer ($NaPO_4$). The fixed samples were stored at 4°C for five months before further analysis. The drying process started with rinsing samples in 0.075 M phosphate buffer before being fixed in 0.5% aqueous osmium tetroxide (OsO_4) for 1–2 h. Samples were rinsed three times with mQ-H_2O, followed by dehydration in ethanol concentration and critical point drying with liquid CO_2. For visualization, samples were mounted onto a stub using double stick, carbon-conductive tape, splattered with a gold-palladium coating and visualised with a JSM840 Joel SEM (Joel, Tokyo, Japan) at 5 kV and a working distance of 12 mm.

2.5. Physiological responses

2.5.1. Respiration rate

Fruit respiration rate was measured as the amount of CO_2 produced by plums using the closed system method as described by Fawole and Opara (2013a), with slight modification. Three randomly selected plums were placed in a 1 L hermetically sealed glass jar for 1 h with a lid containing a rubber septum. After incubation, CO_2 production inside each glass jar was measured from the head space through the rubber septum using an O_2/CO_2 gas analyser (Checkmate 3, PBI Dansensor, Denmark). All measurements were taken in triplicate. Results were presented as the mean ± S.E. (mL CO_2/kg.h) of determinations obtained (n = 3) per treatment for each interval.

2.5.2. Ethylene production

Ethylene production was measured using the closed system method, as described by Fawole and Opara (2013a), with slight modification. Three randomly selected plums were placed in a 1 L hermetically sealed glass jar for 1 h with a lid containing a rubber septum. After incubation, ethylene production was measured from the head space through the rubber septum using an ICA56 Ethylene Analyzer (Fricaval 89, Spain). All measurements were taken in triplicate. Results were presented as the mean ± S.E. (µL C_2H_4/kg.h) of determinations obtained (n = 3) per treatment for each interval.

2.6. Physico-textural properties

2.6.1. Colour attributes

Fruit colour was assessed in the CIELAB coordinates (L*, a*, b*) using a Minolta Chroma Meter CR-400 (Minolta Corp, Osaka, Japan) after calibration with a white tile background (Fawole & Opara, 2013a). Two measurements were taken on opposite sides of the equatorial region (Fig. 1, Appendix) of individual plums. Changes in peel colour were recorded over storage using a constant 10 fruit per treatment, with markings indicating the area for measurement. Fruit flesh colour was assessed using 10 randomly selected fruit per treatment that were peeled with a vegetable peeler. Colour changes during storage were reported using lightness (L*) ranging between L* = 0 (black) and L* = 100 (white). In addition, chroma (C*), which represents colour saturation, was calculated according to equation (1). Results were expressed as mean ± S.E. of determinations obtained (n = 20) per treatment for each interval.

$$\text{Chroma} = (a^{*2}+b^{*2})^{1/2} \quad (1)$$

where a* = redness (positive) to greenness (negative) and b* = yellowness (positive) to blueness (negative)

2.6.2. Textural properties

2.6.2.1. Flesh firmness

Flesh firmness was determined according to the method described by Fawole and Opara (2013a), with modification. Using a firmness analyser (GÜSS-FTA, South Africa) fitted with an 11 mm diameter cylindrical probe and programmed to penetrate 14.5 mm into the test fruit at speed of 10 mm/s, flesh firmness was measured over storage using 10 randomly selected fruit per treatment. Tests were performed in duplicate on fruit peeled with a vegetable peeler on opposite sides of the equatorial region (Fig. 1, Appendix). Peak force (N) required to penetrate plum flesh was taken as flesh firmness.

Results were expressed as mean ± S.E. of determinations obtained (n = 20) per treatment for each interval.

2.6.2.2. Whole fruit firmness

Whole fruit firmness was determined by compression tests using a texture profile analyser (TA.XT *plus*, Stable Micro System, UK), as described by Fawole and Opara (2013a), with modification for plum fruit. Tests were performed with a 35 mm diameter cylindrical compression probe with 1 mm/s pre-test speed, 1 mm/s test speed, 10 mm/s post-test speed, and 0.49030 N trigger force. Ten randomly selected plums per treatment were analysed per interval. Individual fruit were placed horizontally on the platform and whole fruit firmness (N) was considered as the maximum force required for 12 mm compression. Results were expressed as mean ± S.E. of determinations obtained (n = 10) per treatment for each interval.

2.6.2.3. Peel puncture resistance

Peel puncture resistance was measured using a texture profile analyser (TA.XT *plus*, Stable Micro System, UK). Tests were performed in duplicate on opposite sides of the equatorial region of fruit (Fig. 1, Appendix), using a 6 mm diameter cylindrical probe. The operating conditions of the instrument were as follows: pre-test speed 1 mm/s, 1 mm/s test speed, 10 mm/s post-test speed, and 0.49030 N trigger force. Each unpeeled fruit was placed horizontally on a bevelled stand on the platform and peel puncture resistance (N) was considered as the maximum force required for 12 mm penetration into the fruit. Results were expressed as mean ± S.E. of determinations obtained (n = 10) per treatment for each interval (Ozturk *et al*., 2019).

2.7. Chemical properties

2.7.1. Total soluble solids

Total soluble solids (TSS, °Brix) was determined using a digital refractometer (Palette, PR-32 ATAGO, Bellevue, USA) calibrated with distilled water. Pooled juice samples of two fruit per replicate, with five replicates per treatment, were measured. TSS (°Brix) values were reported as the mean ± S.E. of determinations obtained (n = 5) per treatment for each interval (Fawole & Opara, 2013b).

2.7.2. Titratable acidity

Titratable acidity (TA, %) was determined using an automated titrator (Metrohm AG 760, Herisau, Switzerland) according to the method described by Fawole and Opara (2013b). Pooled juice samples

of two fruit per replicate, with five replicates per treatment, were measured. TA was expressed as the percentage of malic acid (%MA) and reported as the mean ± S.E. of determinations obtained (n = 5) per treatment for each interval.

2.7.3. TSS/TA and BrimA

TSS/TA and BrimA were calculated from the TSS and TA values obtained per treatment for each interval. BrimA was calculated according to equation (2).

$$BrimA = TSS - k*TA \quad (2)$$

where TSS = total soluble solids (°Brix), TA = titratable acidity (%MA) and k is the tongue's sensitivity index ranging between 2 - 10 (Fawole & Opara, 2013b), where a k-value of five was used.

Results were expressed as mean ± S.E. of determinations obtained (n = 5) per treatment for each interval.

2.8. Physiological disorders

2.8.1. Weight loss

Ten constant fruit per treatment were weighed individually at each interval throughout storage using an electronic scale (Mettler, Toledo, Switzerland, 0.0001 g accuracy). The weight loss of each fruit was calculated according to equation (3) and reported as the mean ± S.E. of determinations obtained (n = 10) per treatment for each interval (Mphahlele *et al.*, 2016a).

$$\text{Weight loss (\%)} = [(W_i - W_t) \div W_i] \times 100 \quad (3)$$

where W_i is the weight (g) of the fruit at harvest and W_t is the weight (g) of the fruit at the storage interval.

2.8.2. Shrivel and decay incidence

Shrivel incidence was assessed using a constant three cartons of fruit (50 plums per carton) and calculated according to equation (4). A plum was deemed shrivelled when the shrivel extended half way or more over the shoulder of the fruit, as classified by packhouse management (Fig. 2, Appendix). The cumulative mean (%) ± S.E. was reported per treatment for each interval (Kritzinger *et al.*, 2018b).

$$\text{Shrivel incidence (\%)} = \frac{shrivelled\ fruit\ in\ carton}{total\ fruit\ in\ carton} \times 100 \quad (4)$$

Decay incidence was assessed using a constant three cartons of fruit (50 plums per carton) and calculated according to equation (5). The cumulative mean (%) ± S.E. was reported per treatment for each interval (Ali *et al.*, 2010).

$$\text{Decay incidence (\%)} = \frac{decayed\ fruit\ in\ carton}{total\ fruit\ in\ carton} \text{ x } 100 \quad (5)$$

2.9. Volatile analysis

Volatile analysis was performed using the method described by Mphahlele *et al*. (2016b), with modification. Samples were prepared by adding 10 mL of a pooled juice sample (two peeled fruit per replication) into a solid phase micro extraction (SPME) vial, followed by 3 mL 20% NaCl solution and 50 µL anisole-d8 (internal standard), before being vortexed and analysed on the GC-MS instrument by SPME-GC-MS with a gray (divinylbenzene, carboxen and polydimethyl siloxane (DVB/CAR/PDMS)) fiber. Separation was performed on a gas chromatograph (6890N, Agilent technologies network) coupled to an Agilent technologies inert XL EI/CI Mass Selective Detector (MSD) (5975B, Agilent technologies Inc., Palo Alto, CA). The GC-MS system was coupled to a CTC Analytics PAL autosampler. Separation of the plum volatiles was performed on a polar STABILWAX (60 m, 0.25 mm ID, 0.25 µm film thickness) capillary column. Helium was used as the carrier gas at a flow rate of 1 mL/min. The injector temperature was maintained at 240°C. The oven temperature was programmed as follows: 35°C for 5 min; and ramped up to 70°C at a rate of 3°C/min for 3 min; followed by a ramping rate of 4°C/min for 5 min until 120°C and eventually to a maximum temperature of 240°C at a rate of 10°C/min and held for 5 min. The MSD was operated in a full scan mode and the source and quad temperatures were maintained at 230°C and 150°C, respectively. The transfer line temperature was maintained at 250°C. The mass spectrometer was operated under electron impact (EI) mode at ionization energy of 70 eV, scanning from 30 to 500 m/z. All samples were analysed in triplicate. Results were reported as mean peak area percentage at harvest, and at the end of cold storage, at 5 d shelf life and at 20 d shelf life per treatment.

2.10. Phytochemical analysis

2.10.1. Sample extraction

In triplicate (two plums per replication), plums were peeled, segmented and frozen at -80°C at each interval, and then freeze dried and finely ground in a coffee grinder using liquid nitrogen.

For the determination of total phenolic content, total flavonoid content, total anthocyanin content, and antioxidant capacity (%RSA, FRAP, $ABTS^{\bullet+}$), samples were extracted according to the method described by Wang *et al.* (2018), with slight modification. Briefly, 1 g of powdered sample

was mixed with 10 mL of 0.1% HCl (v/v) in 80% methanol, shaken vigorously and sonicated in cold water for 25 min. The mixture was then centrifuged at 4 000 rpm for 15 min at 4°C, and the supernatant collected.

To determine total carotenoid content, samples were extracted according to the method described by Jones *et al*. (2013). Briefly, 74–76 mg of powdered sample was transferred into 2 mL microcentrifuge tubes, along with five glass beads and 700 µL of extraction buffer (0.25% BHT in 95% ethanol). The tubes were vortexed and placed into a hot water bath at 85°C for 10 min after which they were left to cool to room temperature (21°C). The samples were vortexed and centrifuged at 14 000 rpm for 15 min. The supernatant was collected, and the residue was re-extracted following the same procedure. The two supernatants were combined.

For ascorbic acid content determination, samples were extracted according to the method described by Opara *et al*. (2017). Briefly, 1 g of powdered sample was mixed with 9 mL of 1% metaphosphoric acid in 15 mL centrifuge tubes. The tubes were vortexed and sonicated in cold water for 5 min. The tubes were then centrifuged at 4 000 rpm for 20 min at 4°C and the supernatant collected. All sample extracts were stored at 4°C before analysis.

2.10.2. Total phenolic content

Total phenolic content was determined according to the Folin-Ciocalteu method, as described by Tabart *et al*. (2018). Briefly, 20 µL of blank (80% methanol), standard (0–1.2 mM gallic acid) or sample extract (6x dilution) was mixed with 100 µL of 10% Folin-Ciocalteu reagent in a 96-well microplate. After 3 min of incubation at ambient conditions in the dark, 80 µL of sodium carbonate solution (7.5% w/v) was added, and the mixture was incubated at 30°C for 1 h. Absorbance was measured at 750 nm using a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). All measurements were performed in triplicate. The results were expressed as mean ± S.E. of determinations obtained (n = 9) in grams of gallic acid equivalents (GAE) per gram of freeze-dried (FD) sample.

2.10.3. Total flavonoid content

Total flavonoid content was determined using the method described by Herald *et al*. (2012). In a 96-well microplate, distilled water (100 µL) was added to each well, followed by sodium nitrite (10 µL, 50 mg/mL) and 25 µL of blank (80% methanol), standard (0-0.5 mg/mL catechin) or sample extract (6x dilution). After 5 min of incubation in dark, ambient conditions, aluminium chloride (15 µL, 100 mg/mL) was added, and microplates were incubated for a further 6 min in dark, ambient conditions before sodium hydroxide (50 µL, 1M) and distilled water (50 µL) were added. Absorbance

measurements were taken at 517 nm after a 30 s shaking period in a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). All measurements were performed in triplicate. The results were expressed as mean ± S.E. of determinations obtained (n = 9) in milligrams catechin equivalents (CAE) per gram of freeze-dried (FD) sample.

2.10.4. Total anthocyanin content

Total anthocyanin content was determined using the pH differential method as described by Mphahlele *et al*. (2016b). Two different buffer systems were used: one at pH 1.0 (0.1 M HCl/4.9 mM KCl) and another at pH 4.5 (24.8 mM NaAC). Sample extract (150 µL) was added to 1 mL of potassium chloride buffer (pH 1.0) and sodium acetate buffer (pH 4.5), separately. The absorbance of each buffer mixture was measured at 510 nm and 700 nm in a UV–Visible spectrophotometer (Helios Omega, Thermo Fisher Scientific technologies, Madison, USA). Total absorbance and Monomeric Anthocyanin Concentration were calculated according to equations (6) and (7), respectively. All measurements were performed in triplicate. The results were expressed as mean ± S.E. of determinations obtained (n = 9) in micrograms of cyanidin-3-glucoside equivalent (C_3gE) per gram of freeze dried (FD) sample.

Total absorbance (A) = $A_{510}-A_{700}$ (pH 1.0) - $A_{510}-A_{700}$ (pH 4.5) (6)

$$\text{Monomeric Anthocyanin Concentration (MAC)} = \frac{(\text{A x MW x DF})}{\varepsilon \text{ x L}} \quad (7)$$

where A = total absorbance, MW = Cyanidin-3-glucoside molecular weight (449.2 g/mol), DF = Dilution factor (1), ε = Cyanidin-3-glucoside molar absorbance (26 900), L = cell path length (1 cm).

2.10.5. Total carotenoid content

Total carotenoid content was determined according to the method described by Jones *et al*. (2013). In a 96-well microplate, 200 µL of blank (0.25% BHT in 95% ethanol), standard (0-0.16 mg/mL trans-β-carotene) or sample extract was added to each well, and the absorbance was measured at 450 nm in a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). All measurements were performed in triplicate. The results were expressed as mean ± S.E. of determinations obtained (n = 9) in milligrams trans-β-carotene per gram of freeze dried (FD) sample.

2.10.6. Ascorbic acid content

Ascorbic acid content was determined according to the method described by Opara *et al.* (2017), with modification to a microplate assay. In a 96-well microplate, 20 µl of blank (80% methanol), standard

(0-1 mg/mL L-ascorbic acid) or sample extract (10x dilution) was added to 180 µL of 2,6-dichlorophenolindophenol dye (0.025%) before being incubated in the dark for 20 min. Absorbance was measured at 517 nm in a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). To correct for colour interferences, the absorbance of 20 µL sample extract and 180 µL distilled water was measured at 517 nm, and the true absorbance was calculated according to equation (8). All measurements were performed in triplicate. The results were expressed as mean ± S.E. of determinations obtained (n = 9) in milligrams L-ascorbic acid (L-AA) per gram of freeze-dried (FD) sample.

True absorbance = test absorbance – (blank absorbance + sample absorbance) (8)

2.11. Antioxidant capacity

2.11.1. Radical scavenging activity

Radical scavenging activity (%RSA) was measured with a 2,2-Diphenyl-1-picryl-hidrazil (DPPH) radical scavenging method according to Nair *et al.* (2018) with some modifications. A DPPH stock solution was prepared by mixing 98.5 mg DPPH with 250 mL of 100% methanol for 30 min in the dark. The stock solution was stored at -20°C and diluted with 100% methanol (1:9) upon use to generate a working solution.

In a 96-well microplate, 100 µL of blank (80% methanol), standard (0-0.08 mM Trolox) or sample extract (6x dilution, as prepared for phytochemical analysis) was mixed with 200 µL DPPH working solution. After 5 min of incubation in dark, ambient conditions, the absorbance was measured at 520 nm using a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). To correct for colour interferences, the absorbance of 100 µL diluted sample extract and 200 µL 100% methanol was measured at 520 nm and the true absorbance calculated according to equation (8) shown above. All measurements were performed in triplicate. Radical scavenging activity was expressed as mean percentage inhibition of the DPPH radical ± S.E. of determinations obtained (n = 9), as calculated according to equation (9).

%RSA = [1-(true absorbance/blank absorbance)] x 100 (9)

2.11.2. Ferric ion-reducing antioxidant power

Ferric ion-reducing antioxidant power (FRAP) was assessed using the method described by Bolanos De La Torre *et al.* (2015) with modification. Antioxidant capacity was measured through the reaction

of Fe^{2+} with 2,4,6-Tripyridyl-s-Triazine (TPTZ) to form a violet-blue colour with an absorbance maximum at 517 nm.

A FRAP working solution was freshly prepared before analysis by mixing acetate buffer (300 mM, adjusted to pH 3.6 with acetic acid), TPTZ (40mM, dissolved with 40mM HCl) and ferric chloride (20mM in distilled water) in a 10:1:1 proportion. The working solution was warmed at 37°C for 10 min to stabilize the mixture before use.

In a 96-well microplate, 25 µL of blank (80% methanol), standard (0-0.8 mM Trolox) or sample extract (6x dilution, as prepared for phytochemical analysis) and 200 µL working FRAP solution were combined and incubated at 37°C in the dark for 30 min. Absorbance measurements were taken at 517 nm after a 2 min shaking period in a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). All measurements were performed in triplicate. Antioxidant capacity was expressed as mean ± S.E. of determinations obtained (n = 9) in micromoles of Trolox equivalent (µM TE) per gram of freeze-dried (FD) sample.

2.11.3. 2,2'-Azinobis-3-ethylbenzotiazilone-6 sulphonic acid ($ABTS^{\bullet+}$) assay

Antioxidant capacity was further assessed with a 2,2'-Azinobis-3-ethylbenzotiazilone-6-sulphonic acid ($ABTS^{\bullet+}$) assay as described by Chirinos *et al.* (2013). A stock solution was freshly prepared by combining $ABTS^{\bullet+}$ solution (7.4 mM) with potassium persulphate solution (2.6 mM) in a 1:1 proportion and allowing it to react for 12-16 h in dark, ambient conditions. The working solution was prepared by adding 1.5 mL stock solution to 60 mL of 80% methanol to obtain an absorbance of ±0.7 at 750 nm.

In a 96-well microplate, 15 µL of blank (80% methanol), standard (0-0.8 µM Trolox) or sample extract (6x dilution, as prepared for phytochemical analysis) was mixed with 200 µL of $ABTS^{\bullet+}$ working solution, and incubated for 6 min in dark, ambient conditions. Absorbance was measured at 750 nm in a microplate reader (Thermo Fisher Scientific multiskan FC 357, Shanghai, China). All measurements were performed in triplicate. Antioxidant capacity was expressed as mean ± S.E. of determinations obtained (n = 9) in micromoles of Trolox equivalent (µM TE) per gram of freeze-dried (FD) sample.

2.12. Statistical analysis

Data was analysed using a one-way analysis of variance (ANOVA), with coatings being the source of variation. ANOVA-generated p-values and significant differences between means were determined using Duncan's multiple range test with a 95% confidence interval. A factorial ANOVA was also performed to calculate the effects and interaction of the main factors which were treatment

and time interval. All analyses were performed with Statistica software package 13.3 (Tibco Software Inc., California, USA). Linear regressions were performed using XLstat version 7.5.2 (Addinsoft, New York, USA).

3. Results and discussion

3.1. Scanning electron microscopy

Scanning electron microscopy was used to visualise lenticels on the plum surface, as these organelles act as major channels for postharvest moisture loss, as well as points of accelerated respiration (Díaz-Pérez *et al*., 2007). Plums have a waxy cuticle that covers the epicarp and provides a natural protective barrier to high rates of respiration and transpiration (Valero *et al*., 2013). The lenticel of an uncoated plum with the natural wax intact appeared partially covered by the waxy cuticle; however, breaks in the cuticle were visible (Fig. 1A). The cuticular layer tends to be thinner over lenticels, often resulting in cuticular cracking and thus, a reduced ability to control high rates of respiration and moisture loss (Kritzinger & Lötze, 2019). In Fig. 1B, the lenticel of an uncoated plum sample that had been washed and wiped is shown. The plum's lenticel appeared bare, with no waxy cuticle left intact. This is often the result of washing and handling practices that take place in commercial packhouses, rendering the fruit susceptible to higher rates of moisture loss and respiration. In Fig. 1C, the lenticel of a plum coated with a representative coating is shown. The edible coating completely covered the lenticel, and as a result, may provide a barrier to moisture loss and gaseous exchange.

Polysaccharide-based edible coatings are widely reported to be semi-permeable in nature (Baldwin *et al.*, 1999; Rojas-Graü *et al.*, 2007; Hajji *et al*., 2018). It is therefore logical to suggest that the investigated edible coating would not completely inhibit gaseous exchange. This is an important caution in the application of edible coatings, as complete inhibition would result in anaerobic respiration, which would lead to the development of off-flavours (Mahfoudhi & Hamdi, 2015; Thakur *et al.*, 2018).

3.2. Physiological responses

3.2.1. Respiration rate

At harvest, respiration rate was 2.88 mL/kg.h. Respiration rate remained low in the first three weeks of cold storage (2.20 mL/kg.h - 4.14 mL/kg.h), with no significant difference ($p \geq 0.05$) observed between coated plums and control plums (Table 1). At the end of cold storage, plums coated with chitosan had a significantly ($p < 0.05$) higher respiration rate (11.13 mL/kg.h) compared to the other treatments (4.16 mL/kg.h - 6.57 mL/kg.h).

Regardless of treatment, respiration rate increased significantly when plums were moved into shelf life conditions (20°C and 80% RH). At higher temperatures, metabolic activities within the fruit have been reported to increase (Crisosto *et al.*, 1993), thus the need for oxygen is greater and so respiration rate increases. However, coated plums generally had a lower respiration rate than control plums during shelf life. At 5 d shelf life, plums coated with chitosan (19.36 mL/kg.h) had a significantly ($p<0.05$) lower respiration rate than control plums (25.26 mL/kg.h). At 15 d shelf life, respiration rate was lower in all coated plums (16.16 mL/kg.h - 25.23 mL/kg.h) compared to control plums (28.16 mL/kg.h), with the effect being significant ($p<0.05$) in plums coated with alginate (17.49 mL/kg.h), chitosan (16.16 mL/kg.h) and gum arabic (21.68 mL/kg.h). At 20 d shelf life, respiration rate was lower in plums coated with alginate (21.09 mL/kg.h), chitosan (21.52 mL/kg.h), gum arabic (22.84 mL/kg.h), High shine (26.90 mL/kg.h) and Sta-fresh (27.01 mL/kg.h) compared to the control (29.31 mL/kg.h), however, the effect was not significant ($p\geq0.05$).

Edible coatings are widely reported to reduce gaseous exchange by sealing lenticels and covering the epicarp, consequently reducing fruit respiration rate (Maqbool *et al.*, 2011; Díaz-Mula *et al.*, 2012; Kumar *et al.*, 2017; Xin *et al.*, 2017). In this study, the suppressed respiration rate in coated plums could be linked to coating gas barrier properties, which would limit oxygen intake and thus CO_2 production. Similar results were reported for 'Alberta' peaches coated with alginate and stored at 15°C and 40% RH (Maftoonazad *et al.*, 2008), 'Santa Rosa' plums coated with chitosan and stored at 1 ± 1°C and 90 ± 5% RH (Kumar *et al.*, 2017) and sweet cherries coated with gum arabic and stored at 2°C and 90-95% RH (Mahfoudhi & Hamdi, 2015).

3.2.2. Ethylene production

From harvest (0.09 µL/kg.h), ethylene production increased throughout cold storage; however, changes were minimal (0.26 µL/kg.h - 2.57 µL/kg.h) compared to those observed in shelf life (Table 1). Ethylene production increased rapidly throughout shelf life as fruit ripened. In control fruit, ethylene production was 10.08, 10.58, 14.06 and 39.65 µL/kg.h after 5, 10, 15 and 20 d shelf life, respectively. Ethylene production was significantly ($p<0.05$) lower in plums coated with gellan gum (4.12 µL/kg.h), gum arabic (5.82 µL/kg.h), High shine (2.40 µL/kg.h) and Sta-fresh (3.45 µL/kg.h) compared to control plums at 5 d shelf life. At 20 d shelf life, ethylene production was significantly ($p<0.05$) lower in all coated plums (14.27 µL/kg.h - 34.14 µL/kg.h) compared to the control, except for plums coated with Sta-fresh (48.31 µL/kg.h).

Ethylene biosynthesis is a primary characteristic of ripening in climacteric fruit, with high ethylene production initiating the onset of senescence (Zhang *et al.*, 2017). By 20 d shelf life, control plums and plums coated with Sta-fresh had started to senesce (personal observation), corresponding

to high ethylene production. However, ethylene production was reduced in coated fruit as a result of suppressed respiration, which indicated delayed ripening and an extension of shelf life.

Our findings are in agreement with previous studies. Ethylene production in sweet cherries coated with almond gum and gum arabic (Mahfoudhi & Hamdi, 2015) and in plums coated with rice starch (Thakur *et al*., 2018) was reported to be significantly lower than control fruit. The authors reported a shelf life extension in coated fruit, as a result of reduced ethylene production and thus, a delay in fruit ripening.

3.3. Physico-textural properties

3.3.1. Colour attributes

3.3.1.1. Peel colour

At harvest, the peels of 'African Delight™' plums were bright red in colour, with some areas of yellow. As plums ripened, the peel darkened in colour and changed to a deep red-purple shade (Fig. 3, Appendix).

Changes in plum peel colour during cold storage were minimal compared to colour changes observed in shelf life. Chroma did not change significantly ($p \geq 0.05$) from harvest (44.99) to the end of cold storage (43.93 - 48.39), indicating a retention of colour (Fig. 2). Lightness (L*) decreased from harvest (63.91) to the end of cold storage (44.28 – 54.13); however, plums coated with alginate maintained a significantly ($p < 0.05$) higher L* value (54.13) compared to control plums (48.77) at the end of cold storage (Fig. 3).

During shelf life, lightness and chroma decreased as plum peel colour darkened and lost intensity (Fig. 4 and 5). However, lightness in plums coated with alginate (46.28) and chitosan (46.10) was significantly ($p < 0.05$) higher compared to control plums (36.30) at 5 d shelf life. In addition, chroma was significantly ($p < 0.05$) higher in plums coated with alginate (42.49), chitosan (41.57), gellan gum (36.16), gum arabic (38.72) and Sta-fresh (36.84) compared to control plums (32.79) at 5 d shelf life. After 20 d shelf life, colour was retained in plums coated with alginate, chitosan, gum arabic and Sta-fresh, corresponding to a significantly ($p < 0.05$) higher chroma of 25.92, 32.46, 21.50, 16.04, respectively, compared to control plums (10.00). Furthermore, L* in plums coated with alginate (35.81) and chitosan (39.83) was significantly ($p < 0.05$) higher than control plums (32.66) after 20 d shelf life.

During ripening, colour changes in the peel of plums occur as a result of anthocyanin synthesis (Díaz-Mula *et al*., 2009; Kumar *et al.*, 2017). In coated plums, the activity of phenylalanine ammonia-lyase (PAL) and flavanone synthase, two key enzymes in anthocyanin synthesis, may have been

reduced as a result of suppressed respiration, thus delaying colour changes in the peel (Tucker, 1993; Liu *et al.*, 2014).

Similar results have been reported by Valero *et al.* (2013) in four plum cultivars ('Blackamber', 'Golden Globe', 'Larry Ann' and 'Songold') stored at 2°C and 90% RH for 35 days, followed by 20°C and 65% RH for three days. According to the author, plums coated with alginate maintained a significantly higher chroma compared to control plums as a result of suppressed anthocyanin synthesis.

3.3.1.2. Flesh colour

At harvest, plum flesh was yellow in colour, with a chroma of 56.21 and a lightness of 77.75. Flesh colour was retained throughout cold storage in all treatments (Fig. 4 and 5), corresponding to a chroma between 58.64 (alginate) and 60.99 (gum arabic), and a lightness between 78.58 (gellan gum) and 81.77 (gum arabic) at the end of cold storage. There was no significant difference ($p \geq 0.05$) in chroma between treatments at the end of cold storage.

During shelf life, flesh colour darkened slightly and lost saturation, changing to a dull orange shade that corresponded to a decrease in chroma and lightness. However, in plums coated with alginate, chitosan and gum arabic, a lighter, more saturated colour was maintained. At 20 d shelf life, lightness and chroma were significantly ($p<0.05$) higher in plums coated with alginate ($L^* = 80.55$ and $C^* = 60.01$), chitosan ($L^* = 78.05$ and $C^* = 60.18$) and gum arabic ($L^* = 76.87$ and $C^* = 59.74$) compared to control plums ($L^* = 65.48$ and $C^* = 1.11$). Plum flesh colour in coated fruit at 20 d shelf life resembled that of control fruit at 5 d shelf life ($L^* = 75.98$ and $C^* = 61.44$), indicating reduced ripening and a potential shelf life extension.

During ripening, carotenoids are synthesized in the flesh of plums, contributing to the development of a darker orange shade (Valero *et al.*, 2013; Martínez-Romero *et al.*, 2017). In plums coated with alginate, chitosan and gum arabic, the action of enzymes responsible for carotenoid synthesis, such as phytoene synthase and desaturase, and f-carotene desaturase, may have been reduced as a result of suppressed respiration (Marty *et al.*, 2005).

3.3.2. Textural properties

Fruit lost texture throughout storage regardless of treatment, with shelf life conditions accelerating fruit softening. From harvest (49.88 N), flesh firmness decreased throughout cold storage (Table 2). In plums coated with gum arabic, however, flesh firmness was significantly ($p<0.05$) higher (49.69 N) than in control plums (40.29 N) at the end of cold storage. Similarly, plums coated with gum arabic had significantly ($p<0.05$) higher whole fruit firmness (207.72 N) and peel puncture resistance (38.38

N) at the end of cold storage than control fruit, which had a whole fruit firmness of 143.77 N and a peel puncture resistance of 31.80 N at the end of cold storage (Table 3).

Flesh firmness, whole fruit firmness and peel puncture resistance declined rapidly during shelf life. However, flesh firmness was significantly ($p<0.05$) higher in plums coated with alginate (25.42 N), chitosan (29.94 N) and gum arabic (20.06 N) at 20 d shelf life, compared to control fruit (9.12 N). Flesh firmness in plums coated with alginate, chitosan and gum arabic at 20 d shelf life was similar to that of control fruit at 5 d shelf life (26.46 N), indicating the potential of coatings to extend shelf life. Additionally, whole fruit firmness and peel puncture resistance were significantly ($p<0.05$) higher in plums coated with alginate (81.29 N and 21.87 N, respectively) and chitosan (105.16 N and 25.24 N, respectively) at 20 d shelf life, compared to control plums, which had a whole fruit firmness of 36.55 N and peel puncture resistance 7.76 N at 20 d shelf life.

As plums ripen, cell wall hydrolysing enzymes such as β-galactosidase, polygalacturonase, 1,4- β-D-glucanase/glucosidase and pectin methylesterase reduce cell-to-cell adhesion and cell wall mechanical strength, causing a loss of flesh firmness (Maftoonazad *et al.*, 2008; Valero *et al.*, 2013). In shelf life conditions (20°C and 80% RH), enzyme activity has been reported to increase, resulting in a more rapid loss of texture (Zhao *et al*., 2018). In coated plums, the activity of cell wall hydrolysing enzymes may have been reduced as a result of reduced respiration, thus delaying fruit softening over storage (Maftoonazad *et al.*, 2008).

The results of this study are in agreement with Kumar *et al.* (2017), who reported a 78% retention of firmness in plums coated with chitosan and stored at 1 ± 1°C and 90 ± 5% RH for 35 days. The author attributed this effect to significantly lower pectin methylesterase activity in plums coated with chitosan compared to control plums. Furthermore, firmness was better maintained throughout storage (20°C and 80–90% RH for 20 d) in tomatoes coated with gum arabic compared to uncoated tomatoes (Ali *et al.*, 2010).

3.4. Chemical properties

3.4.1. Total soluble solids

Total soluble solids (TSS) was generally maintained in all treatments during storage, despite some slight fluctuations (Table 4). During both cold storage and shelf life, neither treatment, nor time, nor the interaction between the two factors was observed to have a significant effect on TSS ($p\geq0.05$). Similar observations have been reported in chitosan-coated apricots (Ghasemnezhad *et al*., 2010) and alginate-coated and methyl cellulose-coated peaches (Maftoonazad *et al.*, 2008).

3.4.2. Titratable acidity

Titratable acidity (TA) increased from harvest (0.99%) to two weeks cold storage (1.15% - 1.45%), and then declined throughout the rest of storage (Table 4). At the end of cold storage, there was no significant difference ($p \geq 0.05$) in TA between control and coated plums. At 5 d shelf life, however, TA was significantly ($p < 0.05$) higher in plums coated with alginate (0.80%) and chitosan (0.75%) compared to control plums (0.51%). At 20 d shelf life, TA was higher in plums coated with alginate (0.56%), chitosan (0.54%), gellan gum (0.50%), gum arabic (0.56%) and Sta-fresh (0.53%) compared to the control (0.49%), however, the effect was not significant ($p \geq 0.05$).

During ripening, organic acids are used as primary substrates in metabolic processes such as respiration (Valero *et al.*, 2013; Zhang *et al.*, 2018). In coated plums, fruit metabolism may be reduced as a result of suppressed respiration, resulting in higher acidity levels being maintained during ripening. This observation is in agreement with literature, where TA in 'Santa Rosa' plums coated with chitosan (Kumar *et al.*, 2017) and TA in 'Blackamber', 'Golden Globe', 'Larry Ann' and 'Songold' plums coated with alginate (Valero *et al.*, 2013) was higher throughout storage compared to control plums.

3.4.3. TSS/TA and BrimA

TSS/TA in control fruit increased from 16.07 at harvest to 19.56 at the end of cold storage, and BrimA in control fruit increased from 10.91 to 11.66 during the same period (Table 5). TSS/TA was significantly ($p < 0.05$) lower in plums coated with alginate (16.48) at the end of cold storage, however, there was no significant difference ($p \geq 0.05$) in BrimA between control (11.66) and coated fruit (10.54 – 11.73) at the end of cold storage.

At 5 d shelf life, a significant increase in TSS/TA (31.46) and BrimA (13.42) was observed in control plums. However, coated fruit maintained significantly ($p < 0.05$) lower TSS/TA (19.09 - 25.93) and BrimA (10.81 – 11.57) indexes at 5 d shelf life, except for plums coated with High shine. At 20 d shelf life, TSS/TA was lower in plums coated with alginate, chitosan, gellan gum, gum arabic and Sta-fresh, however, the effect was not significant ($p \geq 0.05$). Furthermore, Sta-fresh was the only coating observed to have a significant ($p < 0.05$) effect on BrimA (11.45) compared to control plums (13.15) after 20 d shelf life.

The observed changes in TA throughout storage resulted in changes in the derived indexes of TSS/TA and BrimA. BrimA has been reported as a more accurate indication of fruit flavour compared to TSS/TA, which indicates fruit maturity (Tietel *et al.*, 2011). In climacteric fruit, TSS/TA typically increases during storage as fruit ripen (Nair *et al.*, 2018). In coated fruit, TSS/TA was maintained throughout storage, which may indicate a reduced rate of ripening compared to control fruit. Similar

results were reported in guavas coated with chitosan and alginate that were stored at 10°C and 90–95% RH for 20 days (Nair *et al.*, 2018). BrimA measures the balance between sweetness and sourness using a constant (k) that reflects the tongue's higher sensitivity to TA compared to TSS (Magwaza & Opara, 2015). The lower BrimA maintained in coated plums throughout shelf life compared to control plums could indicate better maintenance of fruit flavour throughout an extended shelf life period. To our knowledge, this is the first time that BrimA has been reported in coated fruit.

3.5. Physiological disorders

3.5.1. Weight loss

Regardless of treatment, weight loss increased throughout storage, with shelf life conditions accelerating losses (Table 6). However, weight loss was generally lower in coated plums compared to control plums. At the end of cold storage, weight loss was significantly ($p<0.05$) reduced in plums coated with High shine (0.63%) compared to the control (1.67%). After 5 d shelf life, weight loss was significantly ($p<0.05$) reduced in plums coated with gellan gum (2.62%), gum arabic (1.99%), High shine (1.61%) and Sta-fresh (1.96%), compared to control plums (3.70%). At 20 d shelf life, these coatings continued to have a significant ($p<0.05$) effect, with plums coated with gellan gum, gum arabic, High shine and Sta-fresh experiencing 5.46%, 4.91%, 4.61% and 7.02% weight loss, respectively, compared to 9.56% weight loss observed in control fruit.

Weight loss can be used as a measure of moisture loss, as moisture loss is reported to account for 97% of the total weight loss experienced by fruit (Díaz-Pérez *et al.*, 2007). Postharvest moisture loss occurs as a result of transpiration and is driven by the vapour pressure deficit that exists between the fruit and the surrounding environment (Kritzinger *et al*., 2018a). In plums coated with gellan gum, gum arabic, High shine and Sta-fresh, a physical barrier to moisture loss may have been created by the coatings, significantly ($p<0.05$) reducing weight loss throughout storage. Our findings are in agreement with previous studies. For instance, gellan gum was found to significantly reduce weight loss in fresh-cut pineapple (Azarakhsh *et al*., 2012) and in gum arabic coated tomatoes, weight loss was significantly reduced after 20 days at 20°C compared to the control (Ali *et al.*, 2010). Furthermore, weight loss was controlled in 'Formosa' plums coated with a carnauba wax-based edible coating containing lemongrass oil (Kim *et al*., 2013).

Interestingly, weight loss in plums coated with alginate and chitosan was greater than in control plums throughout storage. This contradicts the findings of similar studies, whereby alginate was reported to significantly ($p<0.05$) reduce weight loss in 'Blackamber', 'Golden Globe', 'Larry Ann' and 'Songold' plums (Valero *et al.*, 2013) and chitosan was found to significantly ($p<0.05$)

reduce weight loss in ‘Santa Rosa’ (Kumar *et al.*, 2017), ‘Sanhuali’ (Liu *et al.*, 2014) and 'Stanley' and 'Giant' plums (Bal, 2013).

Coating stability may have varied from that of the mentioned studies, due to differences in coating formulation. For instance, vegetable oil was incorporated into the alginate coating in an attempt to increase coating hydrophobicity. However, lipid migration could have occurred during the extended storage period, increasing coating porosity (Reinoso *et al.*, 2008). Consequently, coating moisture barrier properties may have been reduced in comparison to that of the alginate coating used by Valero *et al*. (2013), which did not contain any lipids. Additionally, cultivar differences could have influenced the response of the coatings. Cuticle composition has been found to differ significantly between plum cultivars, directly affecting the moisture barrier properties of the epicarp (Lara *et al.*, 2014; Kritzinger *et al.*, 2019). This may have influenced the ability of alginate and chitosan to control moisture loss in ‘African Delight™’ plums.

3.5.2. Shrivel incidence

At the end of cold storage, shrivel incidence in control plums was 2.52%. In coated plums, shrivel incidence was lower (≤1.86%) than in control plums at the end of cold storage, except for plums coated with chitosan (12.05%) that developed shrivel symptoms at five weeks cold storage (Fig. 6).

At 5 d shelf life, shrivel incidence was lower in all coated plums (0.60% - 4.17%) compared to the control (4.31%), except for plums coated with chitosan (15.55%). At 20 d shelf life, plums coated with gellan gum (1.93%), gum arabic (5.36%), Sta-fresh (2.38%) and High shine (0.60%) were significantly ($p<0.05$) less shrivelled than control plums (23.62%).

Shrivelling in fruit has been linked to moisture loss, resulting from a loss of turgor in the underlying epidermal cells (Vázquez-celestino *et al.*, 2016; Kritzinger *et al.*, 2018a). In this study, a strong positive relationship ($R^2 = 0.653$; $r = 0.808$) was observed between weight loss and shrivel occurrence in ‘African Delight™’ plums. Therefore, the effect of gellan gum, gum arabic, High shine and Sta-fresh on shrivel development can be linked to the moisture barrier properties of the coatings.

Similar studies have reported shrivel to be reduced in ‘Pusa Jwala’ chillies coated with methyl cellulose and stored for eight days at 24 ± 1°C and 70 ± 5% RH (Chaple *et al.*, 2017) and in ‘Bing’ cherries coated with a milk protein-based coating after 20 days storage at 4°C and 80–85% RH (Certel *et al*., 2004).

Plums coated with chitosan has higher shrivel incidence than control plums throughout storage. At 20 d shelf life, shrivel incidence was 52.19% in plums coated with chitosan, compared to 23.62% in control plums. Similar results were observed in ‘Alberta’ peaches coated with chitosan and stored for 60 days at 4°C and 80 ± 2% RH (Hosseini-Farahi *et al.*, 2016). The observed adverse

effect of chitosan on shrivel incidence may be attributed to the inability of chitosan to control moisture loss (Ghasemnezhad *et al*., 2010). Although not clear, chitosan may have modified the biometrics of the fruit cuticle and emphasised the appearance of shrivel as a result of limited coating plasticity (personal observation).

3.5.3. Decay incidence

At the end of cold storage, decay incidence was minimal, measuring 1.33% in control plums and between 0.00% and 0.67% in coated plums. During shelf life, decay incidence increased in all treatments except for plums coated with gellan gum (Fig. 7). After 20 d shelf life, decay incidence was reduced in all coated plums compared to control plums (7.57%), with the effect being significant ($p<0.05$) in plums coated with alginate (1.26%), gum arabic (1.19%) and gellan gum (0.00%).

In contrast to cold storage conditions, shelf life conditions favour microorganism growth (Zagory, 1999). However, coating application controlled decay throughout storage. Similar results were reported for peaches coated with 1% gum arabic and stored at 10°C and 85-90% RH for 32 days (Asghar *et al*., 2014), and strawberries coated with 2% sodium alginate and stored at 20°C and 70 ± 5% RH for five days (Fan *et al*., 2009).

3.6. Volatile analysis

Table 1 (Appendix) shows the relative abundance of compounds detected in the volatile fraction of 'African Delight™' plum juice samples, expressed as mean peak area percentage. A total of 52 volatile compounds were identified in the headspace of the plum juice, with 17 classed as alcohols, seven as aldehydes, 14 as esters, five ketones, one carboxylic acid, one furan, six terpenes and one compound classified as other.

As plums ripen, volatile composition changes both quantitatively and qualitatively, which may result in a change in flavour. In unripe plums, 1-hexanol and (Z)-3-hexanol content is typically high, imparting green aromatic notes (Chai *et al*., 2012; Cuevas *et al*., 2016). At harvest, the mean peak area percentage of 1-hexanol and (Z)-3-hexanol was 53.22% and 14.79%, respectively. Throughout storage, the presence of these volatiles decreased as plums ripened (Fig. 8). In control fruit, peak area percentage of 1-hexanol was 57.21, 16.37 and 3.85% at the end of cold storage, after 5 d shelf life and after 20 d shelf life, respectively, and (Z)-3-hexanol was 19.72, 14.07 and 1.80% at the same intervals (end of cold storage, 5 d shelf life and 20 d shelf life, respectively). Coated fruit were observed to have a similar decreasing trend for both 1-hexanol and (Z)-3-hexanol, with no significant difference ($p\geq0.05$) observed between coated and control plums at the end of cold storage or throughout shelf life.

In a study on 'Bartlett' pears stored in low oxygen and/or high CO_2 conditions, an accumulation of acetaldehyde, ethanol, and ethyl acetate was reported, forming as a result of fruit fermentation (Ke *et al*., 1994). Satora *et al*. (2017) also report acetaldehyde, ethanol and ethyl acetate, as well as methanol and 2-phenyl ethyl acetate in the plum spirits of four varieties of plums ('Wegierka Dabrowicka', 'Wegierka Zwykła', 'Čacanska Lepotica' and 'Stanley'), produced by spontaneous fermentation. Edible coatings have the potential to reduce respiration rates such that oxygen levels within the fruit become too low, resulting in anaerobic respiration. Thus, the detection of such volatiles can be used as a measure of quality, indicating if fermentation occurred in coated fruit.

In this study, acetaldehyde, methanol and 2-phenyl ethyl acetate were not detected, however, ethanol and ethyl acetate were identified. At harvest, the peak area percentage of ethanol was very small (0.70%). No fermentation volatiles should be present at this point, thus the detection of ethanol at harvest may have been a result of sample contamination and can, therefore, be disregarded. Throughout storage, however, ethanol peak area percentage increased significantly ($p<0.05$) in all treatments (Fig. 9). Because sample preparation and conditions of SPME-GC-MS were kept constant, the greater presence of ethanol could be due to fruit fermentation. At the end of cold storage, however, no significant difference ($p\geq0.05$) in ethanol peak area percentage was detected between coated and control plums (Fig. 9). After 5 d shelf life, ethanol peak area percentage was significantly ($p<0.05$) greater in alginate (51.02%), chitosan (54.32%), gum arabic (54.77%) and Sta-fresh-coated fruit (49.88%) than in control plums (19.25%). These coatings may have reduced the fruit's respiration rate to a level whereby anaerobic fermentation was initiated. However, by the end of storage, no significant difference ($p\geq0.05$) was observed between treatments.

Esters such as ethyl acetate, along with propyl acetate, butyl acetate, hexyl acetate and isoamyl acetate have been identified as compounds occurring in fresh plums, but also forming during fermentation (Satora *et al.*, 2017). Thus, it is difficult to determine whether their detection is as a result of fermentation or not. Regardless, no significant difference ($p\geq0.05$) in ethyl acetate peak area percentage was observed between treatments throughout storage (Fig. 9).

Overall, the presence of fermentation volatiles in coated fruit did not differ from control fruit, with the exception of ethanol in plums coated with alginate, chitosan, gum arabic and Sta-fresh at 5 d shelf life. By the end of shelf life, however, no significant difference ($p\geq0.05$) in ethanol peak area percentage was observed between coated and control plums. Furthermore, no significant difference ($p\geq0.05$) in ethyl acetate content was observed between coated and control fruit, and there was an absence of acetaldehyde, methanol and 2-phenyl ethyl acetate in all treatments. Thus, it can be

assumed that oxygen availability was maintained at a high enough level in coated plums such that fermentation was not initiated.

3.7. Phytochemical properties

3.7.1. Total phenolic content

Phenolic compounds form one of the major classes of secondary metabolites produced in plants, greatly contributing to the overall antioxidant capacity of fruit (Amiot *et al.*, 1997). Throughout cold storage, total phenolic content (TPC) increased in all treatments (Table 7), from 4.77 g GAE/g at harvest to between 6.86 g GAE/g (alginate and chitosan) and 9.40 g GAE/g (gellan gum) at the end of cold storage. TPC in plums coated with gellan gum was significantly ($p<0.05$) higher than in control plums at the end of cold storage. Similarly, TPC in gellan gum-coated plums was significantly ($p<0.05$) higher than control plums after 5, 10 and 20 d shelf life, measuring 9.66, 10.45 and 9.70 g GAE/g, respectively, compared to 7.97, 8.47 and 7.84 g GAE/g in control plums for the same storage intervals (5, 10 and 20 d shelf life). In plums coated with alginate and chitosan, TPC was significantly ($p<0.05$) lower than in control plums at 5, 10 and 15 d shelf life.

In plums coated with alginate and chitosan, fruit metabolism may have been reduced as a result of reduced respiration, which could have suppressed the synthesis of phenolic compounds. Similar results were reported in sweet cherries, where fruit coated with 5% alginate had lower TPC than the control (Díaz-Mula *et al.*, 2012). In plums coated with gellan gum, however, conditions of abiotic stress may have been created by the coating, initiating an increase in the synthesis of secondary metabolites within the fruit as a defensive response (Santana-Galvez *et al.*, 2019).

3.7.2. Total flavonoid content

Total flavonoid content (TFC) increased from 3.73 mg CAE/g at harvest to between 6.17 mg CAE/g (chitosan) and 8.33 mg CAE/g (control) at the end of cold storage, with no significant difference ($p\geq0.05$) among treatments between 2-5 weeks cold storage (Table 8). Fluctuations in TFC were observed during shelf life, which could be linked to fruit ripening, as fruit adjusted to changes in the internal and surrounding environment (Yan *et al.*, 2018). TFC was higher in plums coated with High shine than in control plums at 5, 15 and 20 d shelf life, with the effect being significant ($p<0.05$) at 5 d shelf life (High shine = 9.54 mg CAE/g; control = 5.78 mg CAE/g). Similarly, TFC was significantly ($p<0.05$) higher in plums coated with gellan gum at 10 d (10.72 mg CAE/g) and 20 d (10.08 mg CAE/g) shelf life, compared to control plums (7.68 mg CAE/g at 10 d and 5.14 mg CAE/g at 20 d shelf life).

Flavonoids are one of the major polyphenols synthesized as secondary metabolites in fruit, possessing high antioxidant capacity (Brouillard *et al*., 1997). Therefore, the increase in TFC during cold storage can be associated with the observed increase in TPC during cold storage, with a moderate, positive correlation coefficient (r = 0.642) observed between the two measurements. In plums coated with gellan gum and High shine, the synthesis of secondary metabolites may have been stimulated during ripening as a response to abiotic stress conditions created in the plums. In a similar study by Yan *et al.* (2018) on chitosan-coated strawberries, the application of chitosan was reported to induce the biosynthesis of flavonoid as a stress-response to the environmental change.

3.7.3. Total anthocyanin content

Total anthocyanin content (TAC) increased steadily in control fruit from harvest (11.91 µg C_3gE/g) throughout storage, with plums containing 25.66 µg C_3gE/g at the end of cold storage and 26.57 µg C3gE/g after 10 d shelf life (Table 9). In coated fruit, TAC fluctuated throughout storage. However, TAC was significantly ($p<0.05$) higher in plums coated with gellan gum throughout the first three weeks cold storage, and in plums coated with gum arabic, TAC was significantly ($p<0.05$) higher than control plums throughout the cold storage period. Plums coated with alginate maintained a significantly ($p<0.05$) lower TAC than control plums at the end of cold storage, and at 10 and 15 d shelf life.

In yellow-fleshed plum cultivars, anthocyanin content is generally low, with little change during ripening (Díaz-Mula *et al.*, 2011). In this study, however, an increase in anthocyanin content was observed throughout storage. Anthocyanins form part of the larger group of flavonoids (Hertog *et al*., 1997); therefore, the increase in TAC may be associated with the observed increase in TFC.

In plums coated with alginate, anthocyanin synthesis could have been reduced due to suppressed respiration. This, in turn, could have reduced the activity of phenylalanine ammonia-lyase (PAL) and flavanone synthase, two key enzymes in anthocyanin synthesis (Tucker, 1993; Valero *et al.*, 2013; Liu *et al.*, 2014; Kumar *et al.*, 2017). In a similar study, the anthocyanin content of plums was observed to increase throughout storage, however, in alginate-coated plums, this increase was reduced (Valero *et al.*, 2013). The observed anthocyanin accumulation in plums coated with gellan gum and gum arabic during cold storage could be attributed to conditions of abiotic stress created within the coated fruit. Flesh bleeding is a disorder reported to occur in plums in response to postharvest abiotic stress conditions (Manganaris *et al*., 2008), resulting in a diffusion of anthocyanins from the peel into the flesh of the plum (Navarro-Tarazaga *et al*., 2008; Santana-Galvez *et al.*, 2019).

3.7.4. Total carotenoid content

Total carotenoid content (TCC) was maintained from harvest (0.30 mg trans-β-carotene/g) throughout cold storage in all treatments, except for plums coated with gellan gum (0.46 mg trans-β-carotene/g) and gum arabic (0.54 mg trans-β-carotene/g) at two weeks cold storage (Table 10). At the end of cold storage, there was no significant difference ($p \geq 0.05$) in TCC between coated plums (0.26 mg trans-β-carotene/g - 0.34 mg trans-β-carotene/g) and control plums (0.31 mg trans-β-carotene/g).

TCC increased during shelf life, with control plums containing 0.39, 0.48, 0.64 and 0.68 mg trans-β-carotene/g after 5, 10, 15 and 20 d shelf life, respectively. In plums coated with alginate, TCC was significantly ($p<0.05$) lower than in control plums throughout shelf life. Additionally, plums coated with chitosan had a significantly ($p<0.05$) lower TCC than control plums at 15 d and 20 d shelf life. Carotenoid synthesis may have been reduced during ripening in plums coated with alginate and chitosan as a result of suppressed respiration, which may have reduced the activity of the enzymes responsible for carotenoid synthesis such as of phytoene synthase and desaturase, and f-carotene desaturase (Marty *et al*., 2005). Our results are in agreement with those reported by Valero *et al.* (2013), whereby a delay in carotenoid synthesis was observed in alginate-coated plums ('Blackamber', 'Golden Globe', 'Larry Ann' and 'Songold') at the end of storage (2°C and 90% RH for 35 days, followed by 20°C and 65% RH for three days).

3.7.5. Ascorbic acid content

Despite some fluctuations, ascorbic acid content (AAC) was generally maintained throughout storage, with control plums containing 109.34 mg L-AA/g at harvest, 99.72 mg L-AA/g at the end of cold storage, 100.45 mg L-AA/g at 5 d shelf life and 108.53 mg L-AA/g at 20 d shelf life (Table 11). No coating was observed to have a consistent, significant effect on AAC compared to control plums throughout storage.

Several authors have reported AAC to significantly decrease over storage, with coated fruit maintaining higher AAC than control fruit (Dong & Wang, 2018; Nair *et al.*, 2018). However, this trend was not observed in the present study.

3.8. Antioxidant capacity

The antioxidant capacity (AOC) of plums is largely determined by the content of polyphenols, ascorbic acid and carotenoids within the fruit, and may fluctuate during postharvest storage depending on both biotic and abiotic factors (Ali *et al.*, 2013). Radical scavenging activity (%RSA) increased significantly ($p<0.05$) in all treatments from harvest (74.70%) throughout cold storage, however, plums coated with alginate (88.43%) and chitosan (88.37%) had a significantly ($p<0.05$) lower %RSA

than control plums (89.87%) at the end of cold storage (Table 12). Similarly, %RSA was significantly ($p<0.05$) lower in plums coated with alginate (88.15%) and chitosan (88.43%) than control plums (90.55%) at 10 d shelf life.

The ferric ion-reducing antioxidant power (FRAP) of plums increased from harvest (0.96 µM TE/g) throughout cold storage (Table 13). FRAP was highest in control plums at four weeks cold storage (1.70 µM TE/g), and thereafter, decreased to 1.26 µM TE/g at 5 d shelf life. In plums coated with gellan gum, FRAP was significantly ($p<0.05$) higher than in control plums at the end of cold storage (1.90 µM TE/g) and at 5 d (1.83 µM TE/g) and 10 d shelf life (1.51 µM TE/g).

Unlike %RSA and FRAP, AOC measured by $ABTS^{\bullet+}$ was observed to decrease from 25.16 µM TE/g at harvest, to between 20.24 µM TE/g (gellan gum) and 22.09 µM TE/g (Sta-fresh) at the end of cold storage (Table 14). No significant difference ($p\geq0.05$) in $ABTS^{\bullet+}$ was observed between coated and control fruit at the end of cold storage. $ABTS^{\bullet+}$ was generally maintained during shelf life. In plums coated with alginate and chitosan, $ABTS^{\bullet+}$ was significantly ($p<0.05$) higher than in control plums at 5, 10 and 15 d shelf life.

Considering the results of the three methods, %RSA and FRAP may give the best indication of AOC, as they exhibited similar trends throughout storage. According to Matthes and Schmitz-Eiberger (2009), polyphenols are the main source of antioxidants in fruit. TPC was found to have an intermediate positive relationship with DPPH ($r = 0.759$) and FRAP ($r = 0.656$) during cold storage, validating the reliability of these methods to assess AOC.

Plums coated with alginate and chitosan had a lower AOC than control plums throughout storage. Fruit metabolism in plums coated with alginate and chitosan may have been decreased as a result of suppressed respiration, which could have reduced the synthesis of secondary metabolites, consequently reducing AOC. Similar results have been reported by Ahmed *et al*. (2009), whereby the level of total antioxidants in coated nectarines remained lower than in control fruit throughout the ripening period.

Conversely, the higher AOC in plums coated with gellan gum compared to control plums could have occurred as a defensive response to stress conditions created within the coated fruit (Santana-Galvez *et al.*, 2019). In a study by Randome *et al*. (2017), AOC increased in tomatoes when fruit were subjected to different abiotic stresses.

4. Conclusion

Edible coatings had a significant effect on the postharvest quality of ‘African Delight™’ plums. Alginate, chitosan and gum arabic performed best in reducing ripening and delaying physico-chemical changes in fruit throughout storage, as a result of suppressed respiration and ethylene

production. However, alginate and chitosan did not control weight loss and shrivel development, hence leading to postharvest losses. In addition to reducing changes related to ripening, gum arabic significantly ($p<0.05$) reduced weight loss, shrivel development and decay incidence throughout storage. Therefore, gum arabic could be explored as a postharvest edible coating for exported 'African Delight™' plums, with the potential to extend shelf life by up to 15 d.

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Table 1. Physiological responses in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Respiration rate (mL CO_2/kg.h)					Ethylene production (µL C_2H_4/kg.h)				
Cold storage	Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5
Alginate	3.64±0.73^{ab}	2.21± 0.00*	2.22± 0.00*	2.97± 0.74^{c}	4.48± 0.00^{b}	0.50±0.26^{b}	0.53±0.21^{b}	0.62±0.15^{bc}	0.55±0.13^{b}	0.73±0.09^{b}
Chitosan	2.88± 0.72^{b}	2.19± 0.00	2.20± 0.00	5.88± 0.74^{b}	11.13± 1.28^{a}	0.39±0.14^{b}	0.44±0.10^{bc}	0.70±0.13^{b}	0.82±0.25^{b}	0.82±0.37^{b}
Gellan gum	2.47± 0.00^{b}	2.48± 0.00	4.14± 0.83	4.97± 0.00^{b}	4.16± 0.83^{b}	0.26±0.09^{b}	0.43±0.08^{bc}	0.22±0.03^{cd}	0.33±0.02^{b}	0.26±0.02^{b}
Gum arabic	3.96± 0.79^{ab}	2.39± 0.00	2.39± 0.00	4.79± 0.00^{b}	5.61± 0.80^{b}	0.96±0.13^{a}	1.06±0.19^{a}	1.27±0.27^{a}	2.12±0.62^{a}	2.57±0.75^{a}
High shine	2.44± 0.00^{b}	2.45± 0.00	3.27± 0.82	4.91± 0.00^{b}	6.57± 0.82^{b}	0.26±0.04^{b}	0.26±0.05^{bc}	0.30±0.02^{bcd}	0.42±0.06^{b}	0.37±0.07^{b}
Sta-fresh	2.45± 0.00^{b}	3.28± 0.82	4.11± 0.82	5.76± 0.82^{b}	4.96± 0.00^{b}	0.29±0.10^{b}	0.22±0.09^{bc}	0.17±0.01^{d}	0.26±0.05^{b}	0.57±0.17^{b}
Control	4.83± 0.00^{a}	3.24± 0.82	4.05± 0.81	8.12± 0.81^{a}	4.91± 0.00^{b}	0.06±0.03^{b}	0.11±0.02^{c}	0.10±0.01^{d}	0.12±0.02^{b}	0.31±0.05^{b}
Prob. > F										
Treatment	0.0001					< 0.0001				
Time	< 0.0001					< 0.0001				
Treatment x time	< 0.0001					0.0005				
Shelf life	Day 5	Day 10	Day 15	Day 20		Day 5	Day 10	Day 15	Day 20	
Alginate	20.76±1.33^{cd}	26.60±5.64^{a}	17.49±2.10^{cd}	21.09±4.29^{b}		11.23±1.54^{a}	30.67±4.85^{a}	30.74±3.42^{ab}	34.14±1.85^{c}	
Chitosan	19.36±0.77^{d}	22.98±2.10^{a}	16.16±1.62^{d}	21.52±2.98^{b}		10.80±0.65^{a}	19.70±3.47^{abc}	25.01±3.88^{bc}	33.29±1.12^{cd}	
Gellan gum	24.56±0.85^{bcd}	27.52±1.72^{a}	22.54±0.87^{abc}	37.01±8.50^{a}		4.12±0.29^{bc}	13.90±2.50^{bcd}	16.89±1.89^{cd}	30.97±0.16^{d}	
Gum arabic	27.60±2.15^{ab}	27.20±1.43^{a}	21.68±0.83^{bcd}	22.84±2.93^{ab}		5.82±1.18^{b}	16.76±4.39^{bcd}	19.30±3.21^{cd}	25.94±0.05^{e}	
High shine	25.80±0.83^{abc}	32.91±4.38^{a}	24.73±3.41^{ab}	26.90±2.30^{ab}		2.40±0.05^{c}	5.43±0.60^{d}	8.69±0.86^{d}	14.27±0.70^{f}	
Sta-fresh	30.95±3.02^{a}	26.45±3.08^{a}	25.23±0.87^{ab}	27.01±3.12^{ab}		3.45±0.27^{bc}	24.78±6.51^{ab}	36.19±5.68^{a}	48.31±0.27^{a}	
Control	25.26±1.46^{bc}	28.52±2.59^{a}	28.16±1.76^{a}	29.31±3.30^{ab}		10.08±1.53^{a}	10.58±3.06^{cd}	14.06±3.09^{cd}	39.65±0.21^{b}	
Prob. > F										
Treatment	0.0023					< 0.0001				
Time	< 0.0001					< 0.0001				
Treatment x time	0.0392					< 0.0001				

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, respiration rate was 2.88±0.72 mL CO_2/kg.h and ethylene production was 0.09±0.00 µL C_2H_4/kg.h; *not significant.

Table 2. Flesh firmness (N) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	40.52±1.28^{b}	43.29±1.40^{ab}	44.16±1.62*	44.25±2.41^{a}	42.25±2.38^{abc}	42.38±1.83^{a}	44.34± 4.24^{a}	30.65± 2.98^{a}	25.42± 3.57^{ab}
Chitosan	42.28±1.86^{ab}	45.90±2.87^{a}	43.30±2.68	38.94±1.87^{abc}	42.15±1.99^{abc}	39.29±2.98^{a}	40.82± 4.67^{a}	31.05± 5.41^{a}	29.94± 4.26^{a}
Gellan gum	42.41±2.54^{ab}	39.14±1.84^{b}	37.91±1.72	31.67±1.75^{c}	35.99±3.21^{c}	24.52±3.57^{b}	27.96± 4.86^{b}	16.60± 3.31^{b}	6.82± 1.04^{d}
Gum arabic	47.09±2.97^{ab}	39.89±2.91^{ab}	43.88±2.54	45.06±3.45^{a}	49.69±2.97^{a}	26.03±2.33^{b}	27.27± 2.78^{b}	16.03± 1.96^{b}	20.06± 3.26^{bc}
High shine	48.49±3.63^{a}	40.82±1.92^{ab}	42.36±2.35	45.10±3.09^{a}	44.79±3.00^{ab}	15.46±2.16^{c}	14.13± 3.46^{cd}	12.19± 3.78^{bc}	12.53± 3.94^{cd}
Sta-fresh	42.58±1.69^{ab}	43.47±1.53^{ab}	37.74±2.36	35.25±3.18^{bc}	40.90±3.27^{bc}	20.05±3.02^{bc}	17.71± 2.56^{bc}	15.32± 1.80^{b}	11.15± 2.45^{cd}
Control	47.46±2.54^{ab}	43.87±1.42^{ab}	39.51±1.66	42.06±1.62^{ab}	40.29±2.09^{bc}	26.46±2.83^{b}	7.25± 0.45^{d}	5.60± 0.84^{c}	9.12± 1.83^{d}
Prob. > F									
Treatment	< 0.0001					< 0.0001			
Time	< 0.0001					< 0.0001			
Treatment x time	0.0467					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Flesh firmness at harvest was 49.25±0.19 N; *not significant.

Table 3. Whole fruit firmness (N) and peel puncture resistance in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Whole fruit firmness (N)					Peel puncture resistance (N)				
Cold storage	Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5
Alginate	189.58±16.90*	184.56±13.99*	192.90±8.45*	189.24±12.79^{a}	167.96±9.37^{ab}	40.06±1.41^{a}	40.92±1.11^{a}	39.17±1.25^{a}	39.90±1.31^{a}	36.54±1.23^{ab}
Chitosan	159.46±16.90	185.57±15.98	169.73±12.67	179.14±11.06^{ab}	131.30±19.24^{b}	38.25±1.50^{abc}	41.08±1.98^{a}	36.95±0.84^{abc}	40.33±1.16^{a}	34.75±2.10^{ab}
Gellan gum	187.03±14.94	181.62±16.51	167.24±11.27	148.65±11.68^{bc}	155.36±18.56^{b}	40.32±0.98^{a}	37.36±1.21^{ab}	36.66±1.40^{abc}	34.79±1.82^{bc}	31.84±1.56^{b}
Gum arabic	196.26±20.25	189.92±7.98	172.52±13.67	167.86±12.02^{abc}	207.72±11.66^{a}	38.23±1.48^{ab}	40.62±1.29^{a}	35.08±1.20^{bc}	38.02±1.51^{ab}	38.39±1.62^{a}
High shine	147.59±8.00	164.27±9.01	190.90±13.71	172.18±8.18^{abc}	170.05±10.47^{ab}	35.44±0.95^{bc}	39.33±1.76^{ab}	37.67±1.31^{ab}	35.78±0.98^{bc}	33.98±1.37^{ab}
Sta-fresh	195.52±21.66	164.27±9.01	165.78±20.65	137.82±11.59^{c}	155.89±13.38^{b}	39.91±1.50^{a}	35.33±1.34^{b}	33.89±1.15^{c}	32.47±1.52^{c}	35.55±1.99^{ab}
Control	156.45±10.55	183.53±12.32	157.85±12.15	143.07±10.20^{c}	143.77±10.59^{b}	34.44±0.87^{c}	41.21±1.05^{a}	34.92±1.16^{bc}	34.16±1.28^{bc}	31.80±1.44^{b}
Prob. > F										
Treatment	0.0325					< 0.0001				
Time	< 0.0001					< 0.0001				
Treatment x time	0.4028					0.0017				

Shelf life	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20
Alginate	163.94±10.56^{a}	110.31±10.13^{a}	91.61±8.44^{a}	81.29±9.20^{ab}	34.00±1.60^{a}	27.84±2.39^{a}	22.30±1.50^{ab}	21.87±2.48^{a}
Chitosan	151.59±14.31^{a}	117.45±14.65^{a}	91.28±11.80^{a}	105.16±16.90^{ab}	35.18±2.82^{a}	30.86±2.63^{a}	23.14±2.34^{a}	25.24±2.03^{a}
Gellan gum	83.50±5.64^{cd}	70.40±11.47^{ab}	67.29±11.75^{ab}	51.09±10.01^{bc}	20.12±1.01^{cd}	15.26±1.58^{bc}	13.90±1.76^{cd}	8.55±0.68^{b}
Gum arabic	104.18±10.22^{bc}	92.04±15.42^{ab}	85.39±11.97^{a}	65.53±10.14^{bc}	23.42±1.51^{bc}	20.14±2.00^{b}	18.18±2.38^{abc}	12.43±1.56^{b}
High shine	87.29±7.20^{bcd}	89.18±26.83^{ab}	40.49±2.65^{bc}	34.16±10.42^{c}	20.32±1.03^{cd}	19.72±3.19^{b}	10.00±0.51^{de}	7.71±1.18^{b}
Sta-fresh	119.13±17.91^{b}	89.18±13.95^{ab}	77.98±13.15^{a}	46.79±8.74^{c}	25.24±1.56^{b}	19.09±1.49^{b}	17.46±2.26^{bc}	9.07±1.41^{b}
Control	65.74±6.21^{d}	46.63±4.93^{b}	37.51±2.94^{c}	36.55±1.85^{c}	16.80±0.68^{d}	12.51±0.80^{c}	8.28±0.53^{e}	7.76±0.59^{b}
Prob. > F								
Treatment	< 0.0001				< 0.0001			
Time	< 0.0001				< 0.0001			
Treatment x time	0.0003				< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, whole fruit firmness was 199.61±0.73 and peel puncture resistance was 38.95±1.28; *not significant.

Table 4. Total soluble solids (TSS, °Brix) and titratable acidity (TA, % malic acid) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Total soluble solids (TSS, °Brix)					Titratable acidity (TA, % malic acid)				
Cold storage	Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5
Alginate	15.46±1.00*	15.28±0.52*	16.16±0.48^{a}	16.08±0.47^{ab}	15.12±0.85*	1.40±0.12*	1.40±0.08^{bc}	0.77±0.05^{ab}	0.99±0.03^{c}	0.92±0.04*
Chitosan	15.20±0.40	15.78±0.34	15.78±0.21^{ab}	16.82±0.25^{a}	15.12±0.36	1.37±0.08	1.37±0.07^{bc}	0.78±0.05^{ab}	0.97±0.03^{cd}	0.81±0.01
Gellan gum	16.04±0.38	16.48±0.12	15.90±0.38^{ab}	15.38±0.48^{ab}	15.26±0.47	1.35±0.06	1.18±0.04^{a}	0.81±0.02^{ab}	0.70±0.04^{a}	0.87±0.04
Gum arabic	15.50±0.94	16.26±0.34	14.68±0.70^{b}	15.74±0.37^{ab}	15.46±0.40	1.34±0.10	1.22±0.06^{ac}	0.77±0.02^{ab}	0.81±0.04^{ab}	0.83±0.03
High shine	16.42±0.32	16.14±0.42	16.34±0.39^{a}	16.56±0.49^{a}	15.22±0.83	1.25±0.06	1.15±0.06^{a}	0.86±0.04^{b}	0.86±0.06^{bd}	0.83±0.05
Sta-fresh	16.22±0.55	16.30±0.36	16.14±0.28^{a}	15.42±0.79^{ab}	16.10±0.52	1.32±0.07	1.24±0.03^{ac}	0.72±0.03^{a}	0.79±0.03^{ab}	0.87±0.04
Control	15.12±0.79	16.34±0.45	15.34±0.47^{ab}	14.38±0.84^{b}	15.78±0.36	1.32±0.02	1.45±0.04^{b}	0.81±0.06^{ab}	0.77±0.03^{ab}	0.82±0.06
Prob. > F										
Treatment	0.4942					0.0046				
Time	0.4681					< 0.0001				
Treatment x time	0.7871					0.0107				
Shelf life	Day 5	Day 10	Day 15	Day 20		Day 5	Day 10	Day 15	Day 20	
Alginate	15.08±0.48^{a}	14.64±0.77*	14.58±0.53^{ab}	15.78±0.15^{a}		0.80±0.04^{c}	0.69±0.05^{ab}	0.59±0.03^{b}	0.56±0.03^{b}	
Chitosan	15.30±0.45^{a}	15.74±0.15	14.12±0.58^{b}	15.46±0.56^{ab}		0.75±0.06^{c}	0.83±0.03^{b}	0.61±0.04^{b}	0.54±0.02^{b}	
Gellan gum	13.44±0.74^{b}	15.02±0.50	15.18±0.30^{ab}	15.50±0.90^{ab}		0.53±0.02^{ab}	0.71±0.04^{ab}	0.61±0.03^{b}	0.50±0.02^{ab}	
Gum arabic	14.42±0.35^{ab}	14.64±0.74	14.28±0.72^{b}	15.24±0.16^{ab}		0.57±0.05^{ab}	0.68±0.03^{ab}	0.61±0.02^{b}	0.56±0.02^{b}	
High shine	15.94±0.23^{a}	15.68±0.28	15.94±0.25^{a}	15.86±0.29^{a}		0.49±0.02^{b}	0.73±0.09^{ab}	0.50±0.01^{a}	0.43±0.03^{a}	
Sta-fresh	14.58±0.15^{ab}	15.60±0.59	15.20±0.51^{ab}	14.08±0.51^{b}		0.60±0.01^{a}	0.61±0.04^{a}	0.64±0.02^{b}	0.53±0.02^{b}	
Control	15.96±0.69^{a}	15.16±0.34	16.12±0.53^{a}	15.62±0.45^{ab}		0.51±0.02^{ab}	0.61±0.04^{a}	0.58±0.02^{b}	0.49±0.03^{ab}	
Prob. > F										
Treatment	0.3390					< 0.0001				
Time	0.8124					< 0.0001				
Treatment x time	0.2401					< 0.0001				

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, total soluble solids were 15.84±0.73 °Brix, and titratable acidity was 0.99±0.03 % malic acid; *not significant.

Table 5. TSS/TA and BrimA in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	TSS/TA					BrimA				
Cold storage	Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5
Alginate	11.29±0.97^{ab}	11.04±0.67^{b}	21.22±1.04^{ab}	16.32±0.91^{b}	16.48±0.41^{b}	8.47±0.91*	8.28±0.58^{d}	12.31±0.35^{a}	11.12±0.56*	10.54±0.68*
Chitosan	11.15±0.45^{b}	11.56±0.38^{b}	20.66±1.47^{ab}	17.52±0.82^{b}	18.59±0.47^{ab}	8.33±0.30	8.91±0.21^{cd}	11.89±0.26^{ab}	11.99±0.38	11.05±0.35
Gellan gum	12.06±0.83^{ab}	14.07±0.44^{a}	19.84±1.00^{ab}	22.30±0.93^{a}	17.69±0.74^{ab}	9.31±0.61	10.60±0.22^{a}	11.87±0.46^{ab}	11.90±0.33	10.92±0.44
Gum arabic	11.65±0.39^{ab}	13.49±0.69^{a}	18.98±0.82^{b}	19.59±0.66^{ab}	18.78±0.81^{ab}	8.82±0.58	10.17±0.39^{abc}	10.81±0.66^{b}	11.70±0.26	11.32±0.40
High shine	13.22±0.48^{a}	14.15±0.63^{a}	19.10±0.63^{b}	19.48±1.17^{ab}	18.50±0.50^{ab}	10.17±0.26	10.39±0.34^{ab}	12.04±0.28^{ab}	12.25±0.51	11.09±0.59
Sta-fresh	12.33±0.40^{ab}	13.25±0.56^{a}	22.48±0.98^{a}	19.55±1.25^{ab}	18.51±0.67^{ab}	9.60±0.34	10.12±0.49^{abc}	12.53±0.31^{a}	11.45±0.81	11.73±0.44
Control	11.42±0.45^{ab}	11.31±0.59^{b}	19.20±0.80^{b}	18.72±1.36^{a}	17.03±3.07^{a}	8.51±0.70	9.08±0.62^{bcd}	11.30±0.30^{ab}	10.52±0.86	11.66±0.29
Prob. > F										
Treatment	0.0542					0.0183				
Time	< 0.0001					< 0.0001				
Treatment x time	0.7189					0.4707				

Shelf life	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20
Alginate	19.09±1.02^{d}	21.55±1.31^{ab}	24.64±0.77^{bc}	28.41±1.52^{b}	11.10±0.50^{b}	11.20±0.64*	11.61±0.44^{b}	12.97±0.16^{ab}
Chitosan	20.80±1.23^{cd}	19.09±0.61^{b}	23.55±1.57^{c}	28.58±1.57^{b}	11.55±0.17^{b}	11.60±0.19	11.08±0.58^{b}	12.74±0.59^{ab}
Gellan gum	25.64±1.62^{b}	21.30±1.26^{ab}	25.12±1.45^{bc}	31.34±1.84^{b}	10.81±0.75^{b}	11.46±0.55	12.13±0.40^{ab}	13.02±0.88^{a}
Gum arabic	25.93±2.11^{b}	21.91±1.94^{ab}	23.36±1.08^{c}	27.30±1.28^{b}	11.57±0.35^{b}	11.25±0.87	11.22±0.69^{b}	12.43±0.25^{ab}
High shine	33.01±1.40^{a}	22.64±2.21^{ab}	31.84±1.05^{a}	37.81±2.90^{a}	13.51±0.23^{a}	12.04±0.30	13.43±0.28^{a}	13.72±0.32^{a}
Sta-fresh	24.17±0.48^{bc}	25.63±1.18^{a}	23.93±0.65^{c}	26.76±0.30^{b}	11.56±0.15^{b}	12.53±0.52	12.02±0.45^{ab}	11.45±0.43^{b}
Control	31.46±0.70^{a}	25.14±1.31^{a}	28.07±1.63^{b}	31.92±1.47^{b}	13.42±0.59^{a}	12.11±0.34	13.23±0.58^{a}	13.15±0.38^{a}
Prob. > F								
Treatment	< 0.0001				0.0092			
Time	< 0.0001				< 0.0001			
Treatment x time	< 0.0001				0.1215			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, TSS/TA was 16.07±0.65 and BrimA was 10.91±0.66; *not significant.

Table 6. Weight loss (%) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	0.87±0.10^{b}	1.58±0.18^{a}	1.96±0.24^{a}	2.23±0.28^{a}	2.60±0.34^{a}	4.68±0.52^{b}	5.87±0.61^{b}	6.96±0.69^{b}	8.33±0.83^{ab}
Chitosan	1.19±0.13^{a}	1.95±0.21^{b}	2.33±0.26^{a}	2.58±0.31^{a}	3.21±0.40^{a}	6.16±0.71^{a}	7.72±0.82^{a}	9.02±0.95^{a}	10.62±1.09^{a}
Gellan gum	0.34±0.04^{de}	0.75±0.06^{de}	0.97±0.09^{c}	1.09±0.10b	1.43±0.10^{b}	2.62±0.17^{c}	3.73±0.22^{c}	4.30±0.25^{c}	5.46±0.31^{cd}
Gum arabic	0.25±0.03^{cde}	0.56±0.04^{cde}	0.73±0.06^{bc}	0.87±0.09^{bc}	1.10±0.10^{bc}	1.99±0.17^{c}	3.09±0.22^{c}	3.91±0.29^{c}	4.91±0.35^{cd}
High shine	0.10±0.02^{c}	0.32±0.04^{c}	0.36±0.04^{b}	0.41±0.04^{c}	0.63±0.07^{c}	1.61±0.16^{c}	2.61±0.23^{c}	3.37±0.30^{c}	4.61±0.40^{d}
Sta-fresh	0.20±0.02^{cd}	0.51±0.03^{cd}	0.66±0.05^{bc}	0.78±0.07^{bc}	1.09±0.09^{bc}	1.96±0.16^{c}	3.36±0.30^{c}	4.67±0.83^{c}	7.02±1.18^{bc}
Control	0.44±0.05^{e}	0.87±0.08^{e}	0.95±0.09^{c}	1.10±0.12^{b}	1.67±0.20^{b}	3.70±0.36^{b}	5.54±0.51^{b}	6.81±0.60^{b}	9.56±0.77^{a}
Prob. > F									
Treatment	< 0.0001					< 0.0001			
Time	< 0.0001					< 0.0001			
Treatment x time	< 0.0001					0.0328			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant.

Table 7. Total phenolic content (g GAE/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	6.02±0.53*	5.57±0.45*	6.78±0.32^{a}	5.81±0.42^{c}	6.86±0.39^{c}	5.83±0.15^{d}	6.89±0.55^{e}	7.34±0.41^{c}	7.77±0.20^{ab}
Chitosan	5.54±0.18	6.55±0.23	6.94±0.41^{a}	6.89±0.48^{bc}	6.86±0.35^{c}	6.90±0.30^{cd}	6.68±0.50^{e}	7.62±0.34^{c}	7.13±0.53^{ab}
Gellan gum	6.13±0.12	6.01±0.74	8.19±0.24^{a}	7.38±0.27^{ab}	9.40±0.54^{a}	9.66±0.98^{a}	10.45±0.32^{a}	7.99±0.45^{c}	9.70±0.62^{a}
Gum arabic	6.17±0.25	6.03±0.62	7.78±0.44^{a}	6.48±0.69^{bc}	7.41±0.31^{bc}	7.78±0.16^{bc}	8.16±0.10^{cd}	9.88±0.16^{b}	7.82±0.37^{ab}
High shine	5.91±0.28	6.97±0.32	6.97±0.18^{a}	7.09±0.22^{bc}	8.26±0.25^{b}	7.91±0.38^{bc}	7.25±0.13^{de}	10.44±0.34^{ab}	7.88±0.18^{ab}
Sta-fresh	5.22±0.20	6.43±0.60	5.06±0.89^{b}	8.47±0.31^{a}	7.34±0.33^{bc}	8.90±0.34^{ab}	9.55±0.46^{ab}	7.57±0.12^{c}	6.75±0.31^{b}
Control	5.42±0.47	6.92±0.66	7.55±0.43^{a}	7.33±0.42^{ab}	7.79±0.18^{bc}	7.97±0.28^{bc}	8.47±0.40^{bc}	11.16±0.36^{a}	7.84±0.61^{ab}
Prob. > F									
Treatment	0.0003					< 0.0001			
Time	< 0.0001					< 0.0001			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Total phenolic content at harvest was 4.77±0.23 g GAE/g; *not significant.

Table 8. Total flavonoid content (mg CAE/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	4.93±0.32^{abc}	4.60±0.48*	7.27±0.93*	5.28±0.51*	6.48±0.60*	5.27±0.35^{c}	7.42±1.36b^{c}	5.84±0.38^{b}	8.45±1.55^{ab}
Chitosan	4.41±0.09^{c}	6.11±0.26	6.19±0.70	6.32±0.81	6.17±0.36	6.64±0.76^{bc}	5.09±0.45^{c}	5.98±0.56^{b}	6.65±1.06^{ab}
Gellan gum	5.23±0.24^{ab}	6.75±1.59	7.30±0.96	6.49±0.48	7.39±0.66	8.25±0.99^{ab}	10.72±1.49^{a}	6.62±0.96^{ab}	10.08±1.41^{a}
Gum arabic	5.73±0.17^{a}	6.02±0.96	7.72±0.73	6.06±0.88	6.98±0.63	6.78±1.04^{bc}	6.80±0.93^{bc}	8.64±1.02^{ab}	5.91±0.60^{ab}
High shine	4.79±0.28^{bc}	7.67±1.36	5.16±0.38	6.35±0.54	7.97±0.64	9.54±1.59^{a}	6.61±0.66^{bc}	9.83±1.61^{a}	8.46±2.52^{ab}
Sta-fresh	5.24±0.20^{ab}	6.52±0.91	5.54±1.05	6.93±0.31	6.74±0.88	6.56±0.30^{bc}	8.46±1.13^{ab}	9.70±2.02^{a}	5.04±0.72^{b}
Control	4.72±0.39^{bc}	7.04±1.19	7.00±0.75	6.44±0.26	8.33±1.49	5.78±0.50^{bc}	7.68±0.50^{bc}	8.59±0.50^{ab}	5.14±0.57^{b}
Prob. > F									
Treatment	0.2720					0.0015			
Time	< 0.0001					0.4860			
Treatment x time	0.5366					0.0124			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Total flavonoid content at harvest was 3.73±0.27 mg CAE/g; *not significant.

Table 9. Total anthocyanin content (µg MAC/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	21.23±2.98^{cd}	15.64±2.39^{c}	17.27±1.65^{c}	19.93±0.65^{cd}	21.80±1.19^{c}	25.85±0.36^{cd}	23.58±0.96^{c}	22.75±0.85^{b}	21.26±0.68^{ab}
Chitosan	24.32±0.47^{acd}	19.78±0.34^{cd}	22.36±0.42^{d}	16.16±2.37^{a}	22.08±0.48^{c}	26.22±1.36^{c}	24.73±0.80^{bc}	28.74±1.01^{acd}	27.22±0.86^{ab}
Gellan gum	26.24±0.58^{a}	29.28±1.24^{a}	23.71±0.58^{d}	17.53±0.53^{ac}	22.54±0.46^{c}	26.59±0.64^{c}	25.96±0.55^{bc}	26.14±0.96^{c}	29.71±0.46^{b}
Gum arabic	31.19±0.62^{b}	25.23±2.79^{ab}	31.32±0.36^{a}	27.13±1.46^{b}	31.84±0.99^{a}	27.14±0.53^{c}	28.85±0.59^{a}	29.80±0.56^{ad}	20.87±2.89^{ab}
High shine	20.58±1.90^{c}	17.42±0.59^{cd}	20.21±0.54^{b}	23.34±0.61^{d}	23.27±1.47^{bc}	17.70±0.34^{b}	25.35±0.46^{bc}	30.34±1.02^{d}	26.68±2.47^{ab}
Sta-fresh	25.38±0.34^{ad}	21.28±1.12^{bd}	17.98±0.29^{c}	21.52±0.67^{d}	24.38±0.85^{bc}	22.51±0.47^{a}	24.97±1.42^{bc}	26.89±1.15^{ac}	18.72±0.97^{a}
Control	21.69±0.31^{cd}	18.20±1.28^{cd}	17.70±0.33^{c}	19.80±0.72^{cd}	25.66±0.45^{b}	23.84±1.05^{ad}	26.57±0.35^{ab}	28.44±1.30^{acd}	29.58±6.16^{b}
Prob. > F									
Treatment	< 0.0001					< 0.0001			
Time	< 0.0001					0.0001			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Total anthocyanin content at harvest was 11.91±1.00 µg MAC/g; *not significant.

Table 10. Total carotenoid content (mg trans-β-carotene/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	0.32±0.01^{c}	0.27±0.03^{b}	0.26±0.01^{bc}	0.33±0.03^{bc}	0.26±0.02^{b}	0.26±0.02^{c}	0.33±0.03^{c}	0.31±0.02^{b}	0.41±0.03^{c}
Chitosan	0.26±0.01^{b}	0.23±0.01^{b}	0.28±0.01^{bc}	0.30±0.04^{ac}	0.31±0.02^{ab}	0.34±0.02^{bc}	0.58±0.08^{b}	0.48±0.03^{cd}	0.50±0.07^{cd}
Gellan gum	0.30±0.01^{bc}	0.46±0.06^{a}	0.24±0.02^{c}	0.27±0.02^{ac}	0.26±0.03^{ab}	0.46±0.06^{a}	0.53±0.02^{b}	0.45±0.02^{c}	0.57±0.05^{ad}
Gum arabic	0.39±0.02^{a}	0.54±0.07^{a}	0.36±0.02^{a}	0.34±0.02^{bc}	0.34±0.03^{a}	0.29±0.02^{c}	0.40±0.02^{ac}	0.58±0.05^{ad}	0.77±0.03^{b}
High shine	0.32±0.01^{c}	0.25±0.01^{b}	0.29±0.03^{bc}	0.24±0.01^{a}	0.29±0.02^{ab}	0.46±0.02^{a}	0.39±0.01^{ac}	0.55±0.01^{acd}	0.50±0.04^{cd}
Sta-fresh	0.33±0.02^{c}	0.23±0.01^{b}	0.26±0.01^{bc}	0.39±0.03^{b}	0.29±0.01^{ab}	0.34±0.02^{bc}	0.48±0.04^{ab}	0.50±0.05^{cd}	0.58±0.05^{ad}
Control	0.26±0.03^{b}	0.29±0.01^{b}	0.30±0.02^{b}	0.33±0.03^{bc}	0.31±0.02^{ab}	0.39±0.01^{ab}	0.48±0.02^{ab}	0.64±0.02^{a}	0.68±0.05^{ab}
Prob. > F									
Treatment	< 0.0001					< 0.0001			
Time	0.0193					< 0.0001			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Carotenoid content at harvest was 0.30±0.02 mg trans-β-carotene/g; *not significant.

Table 11. Ascorbic acid content (mg L-AA/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	118.45±1.05^{a}	113.31±0.73^{b}	113.62±1.37^{a}	100.12±4.02^{b}	116.25±2.24^{a}	106.36±4.99^{ab}	102.01±2.81^{b}	109.59±2.27^{a}	108.30±3.03*
Chitosan	117.47±0.68^{ab}	113.69±0.43^{b}	114.04±1.37^{a}	112.38±2.50^{a}	96.32±3.53^{c}	110.52±1.11^{a}	107.07±3.73^{ab}	109.79±1.44^{a}	112.48±1.71
Gellan gum	115.86±0.54^{b}	112.11±0.79^{bc}	109.56±1.47^{a}	109.81±4.62^{ab}	103.06±1.23^{bc}	103.80±1.15^{ab}	110.19±1.81^{a}	104.88±2.38^{ab}	105.99±2.80
Gum arabic	117.42±1.08^{ab}	109.31±0.92^{c}	112.00±0.67^{a}	112.58±0.88^{a}	103.95±1.34^{bc}	103.06±2.51^{ab}	107.12±1.52^{ab}	98.71±4.15^{b}	107.12±1.44
High shine	117.72±0.90^{ab}	104.17±1.61^{d}	112.71±1.02^{a}	106.99±4.67^{ab}	97.98±6.45^{bc}	105.08±1.30^{ab}	111.48±1.20^{a}	109.79±2.07^{a}	110.70±3.67
Sta-fresh	116.44±0.36^{ab}	116.84±1.03^{a}	110.90±3.16^{a}	107.12±1.23^{ab}	107.09±0.96^{b}	108.13±0.83^{ab}	102.26±1.42^{b}	98.83±3.60^{b}	108.50±1.59
Control	117.97±0.36^{ab}	112.79±0.98^{b}	97.68±7.42^{b}	109.69±1.98^{ab}	99.72±1.29^{bc}	100.45±2.76^{b}	113.39±2.25^{a}	108.30±4.15^{a}	108.53±1.87
Prob. > F									
Treatment	0.0374					0.1617			
Time	< 0.0001					0.0030			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Ascorbic acid content at harvest was 109.34±1.42 mg L-AA/g; *not significant.

Table 12. Radical scavenging activity (%RSA), based on 2,2-Diphenyl-1-picryl-hidrazil (DPPH) radical scavenging method, in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	76.14±4.47*	73.72±4.12^{b}	86.53±1.01^{a}	85.21±1.10^{ab}	88.43±0.39^{b}	87.06±0.36^{c}	88.15±0.56^{c}	87.69±1.10^{abc}	85.08±0.63*
Chitosan	79.00±1.11	85.21±0.32^{a}	86.30±1.07^{a}	85.60±2.02^{ab}	88.37±0.27^{b}	89.45±0.27^{ab}	88.43±0.67^{bc}	87.63±0.72^{abc}	85.08±1.57
Gellan gum	82.31±0.78	84.03±1.73^{a}	88.12±0.41^{a}	88.53±0.36^{a}	90.70±0.15^{a}	88.88±0.28^{b}	89.43±0.35^{ab}	88.09±1.47^{abc}	87.43±0.22
Gum arabic	81.82±1.00	83.21±1.62^{a}	88.12±0.55^{a}	82.20±3.52^{b}	89.82±0.10^{a}	89.45±0.23^{ab}	89.81±0.33^{a}	89.74±0.58^{ab}	82.39±4.32
High shine	80.51±1.53	87.54±0.47^{a}	87.98±0.30^{a}	88.55±0.20^{a}	89.64±0.99^{ab}	89.77±0.08^{a}	89.73±0.18^{a}	87.29±1.83^{bc}	82.02±1.64
Sta-fresh	82.31±0.72	85.45±0.96^{a}	80.06±3.20^{b}	89.09±0.32^{a}	89.74±0.28^{a}	90.03±0.19^{a}	89.43±0.16^{ab}	85.71±0.84^{c}	86.23±0.74
Control	77.48±1.19	86.43±0.99^{a}	88.81±0.52^{a}	88.89±0.39^{a}	89.87±0.16^{a}	90.14±0.10^{a}	90.55±0.21^{a}	91.07±0.43^{a}	82.55±2.19
Prob. > F									
Treatment	< 0.0001					0.1660			
Time	< 0.0001					< 0.0001			
Treatment x time	< 0.0001					0.0182			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Antioxidant capacity (DPPH) at harvest was 74.70±1.11%; *not significant.

Table 13. Ferric ion-reducing antioxidant power (µM TE/g) in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	1.02±0.05^{abc}	0.92±0.03^{b}	1.21±0.07^{b}	1.45±0.07^{b}	1.59±0.09^{c}	1.27±0.03^{c}	1.07±0.08^{c}	1.00±0.04^{b}	1.05±0.06^{bcd}
Chitosan	0.99±0.02^{bc}	1.08±0.07^{ab}	1.14±0.04^{bc}	1.75±0.09^{a}	1.59±0.06^{bc}	1.40±0.05^{bc}	1.11±0.04^{c}	1.00±0.04^{b}	0.96±0.06^{cde}
Gellan gum	1.13±0.03^{a}	1.19±0.09^{a}	1.23±0.02^{b}	1.69±0.05^{ab}	1.90±0.13^{a}	1.83±0.16^{a}	1.51±0.05^{a}	0.99±0.09^{b}	1.15±0.10^{bc}
Gum arabic	1.14±0.04^{a}	1.11±0.05^{a}	1.30±0.07^{ab}	1.43±0.15^{b}	1.55±0.03^{c}	1.54±0.09^{b}	1.19±0.03^{bc}	1.36±0.07^{a}	0.85±0.08^{de}
High shine	1.07±0.06^{ab}	1.25±0.04^{a}	1.13±0.06^{bc}	1.64±0.06^{ab}	1.81±0.05^{ab}	1.58±0.07^{b}	1.11±0.04^{c}	1.48±0.06^{a}	0.81±0.06^{e}
Sta-fresh	0.99±0.03^{bc}	1.23±0.07^{a}	0.90±0.06^{c}	1.87±0.08^{a}	1.52±0.05^{c}	1.39±0.04^{bc}	1.32±0.06^{b}	1.14±0.05^{b}	1.24±0.05^{b}
Control	0.89±0.06^{c}	1.21±0.03^{a}	1.57±0.21^{a}	1.70±0.10^{ab}	1.63±0.05^{bc}	1.26±0.03^{c}	1.28±0.05^{b}	1.51±0.07^{a}	1.51±0.10^{a}
Prob. > F									
Treatment	0.0013					< 0.0001			
Time	< 0.0001					< 0.0001			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Antioxidant capacity (FRAP) at harvest was 0.96±0.04 µM TE/g; *not significant.

Table 14. Antioxidant capacity (µM TE/g), based on 2,2'-Azinobis-3-ethylbenzotiazilone-6-sulphonic acid ($ABTS^{\bullet+}$) assay, in 'African Delight™' plum samples during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days)

Treatment	Cold storage					Shelf life			
	Week 1	Week 2	Week 3	Week 4	Week 5	Day 5	Day 10	Day 15	Day 20
Alginate	23.96±1.29^{abc}	24.04±0.91^{a}	21.18±0.45^{b}	22.93±0.53^{ab}	21.58±0.43^{a}	22.99±0.39^{a}	22.51±0.66^{b}	22.17±0.53^{a}	21.06±0.18^{de}
Chitosan	25.12±0.21^{a}	21.03±0.26^{b}	21.59±0.30^{b}	22.30±0.68^{ab}	21.20±0.30^{ab}	22.25±0.37^{a}	24.25±0.97^{a}	21.55±0.29^{ab}	23.47±0.26^{b}
Gellan gum	23.03±0.40^{bcd}	22.24±0.88^{ab}	20.46±0.33^{b}	21.56±0.52^{b}	20.24±0.36^{b}	20.92±0.74^{b}	19.95±0.09^{d}	21.58±0.38^{ab}	20.57±0.31^{e}
Gum arabic	21.73±0.35^{d}	22.84±0.78^{ab}	20.58±0.35^{b}	24.09±1.79^{a}	22.04±0.37^{a}	20.82±0.30^{b}	20.81±0.10^{cd}	20.35±0.24^{c}	22.31±0.48^{c}
High shine	22.32±0.55^{bcd}	21.66±0.25^{b}	20.79±0.15^{b}	21.10±0.31^{b}	21.39±0.36^{a}	20.75±0.23^{b}	21.93±0.21^{bc}	20.63±0.28^{bc}	21.95±0.38^{cd}
Sta-fresh	22.07±0.33^{cd}	22.59±0.48^{ab}	25.27±1.91^{a}	20.43±0.26^{b}	22.09±0.38^{a}	20.39±0.23^{b}	20.99±0.28^{cd}	22.12±0.22^{a}	25.96±0.60^{a}
Control	24.05±0.58^{ab}	21.80±0.31^{b}	21.18±0.53^{b}	21.35±0.54^{b}	21.21±0.30^{ab}	20.84±0.28^{b}	20.77±0.23^{cd}	19.97±0.24^{c}	24.35±0.49^{b}
Prob. > F									
Treatment	0.0316					< 0.0001			
Time	< 0.0001					< 0.0001			
Treatment x time	< 0.0001					< 0.0001			

Means±standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Antioxidant capacity ($ABTS^{\bullet+}$) at harvest was 25.16±0.55 µM TE/g; *not significant.

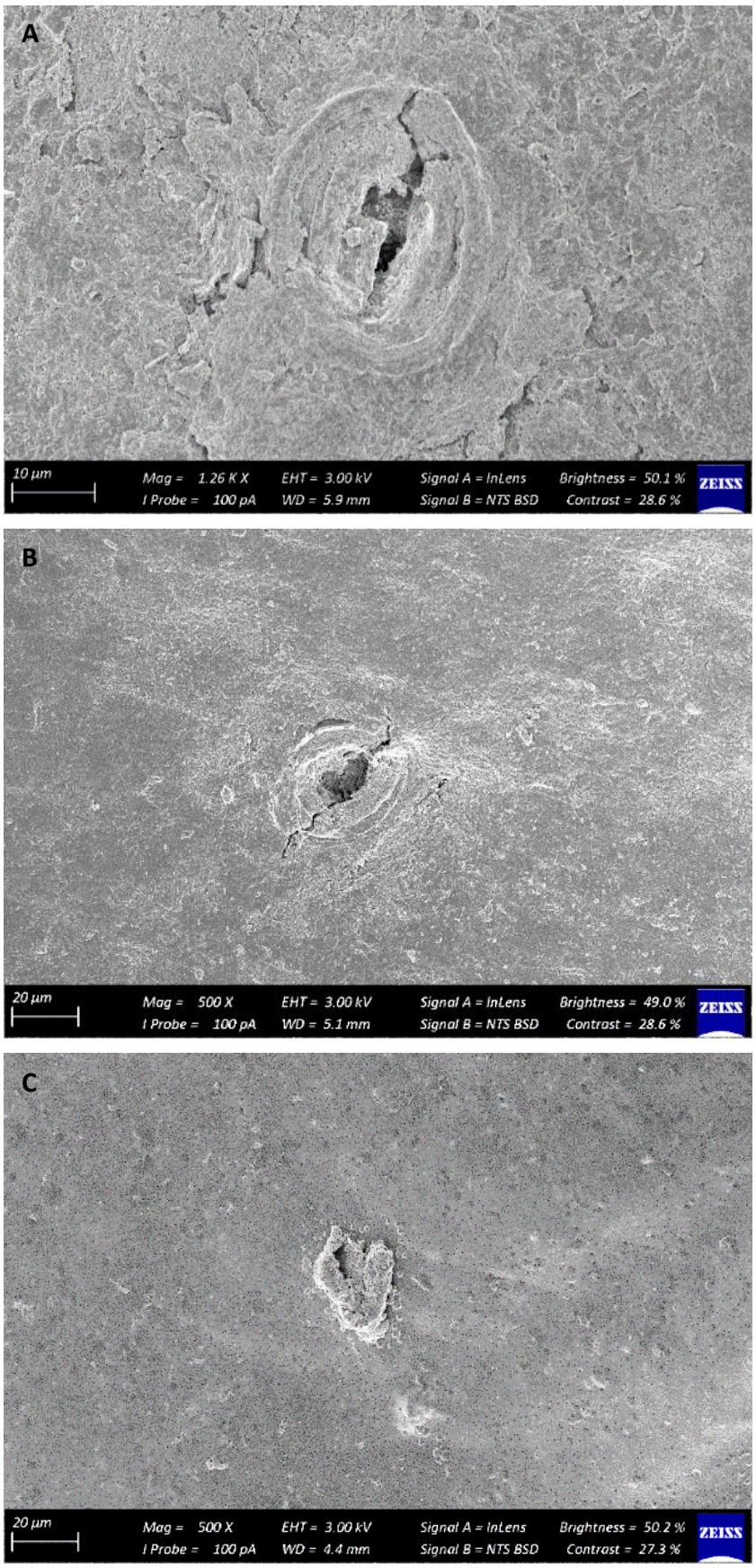

Figure 1. Scanning electron micrographs visualising lenticels of 'African Delight™' plum, where A) uncoated fruit with natural wax intact, B) uncoated fruit with natural wax removed and C) fruit coated with a representative edible coating.

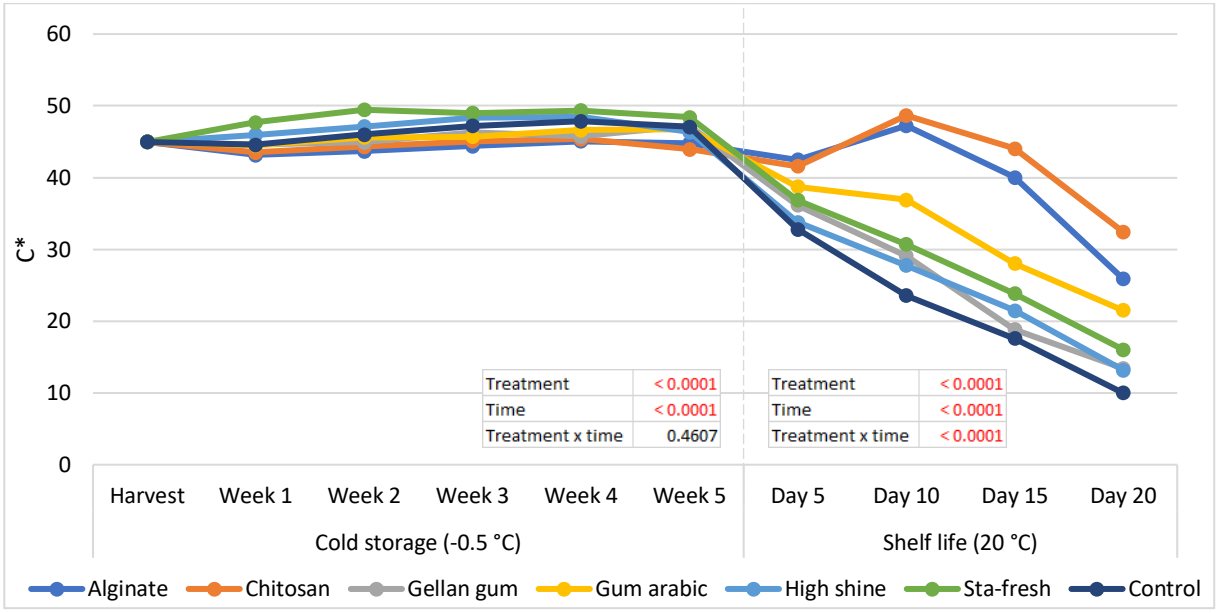

Figure 2. Peel chroma (C*) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

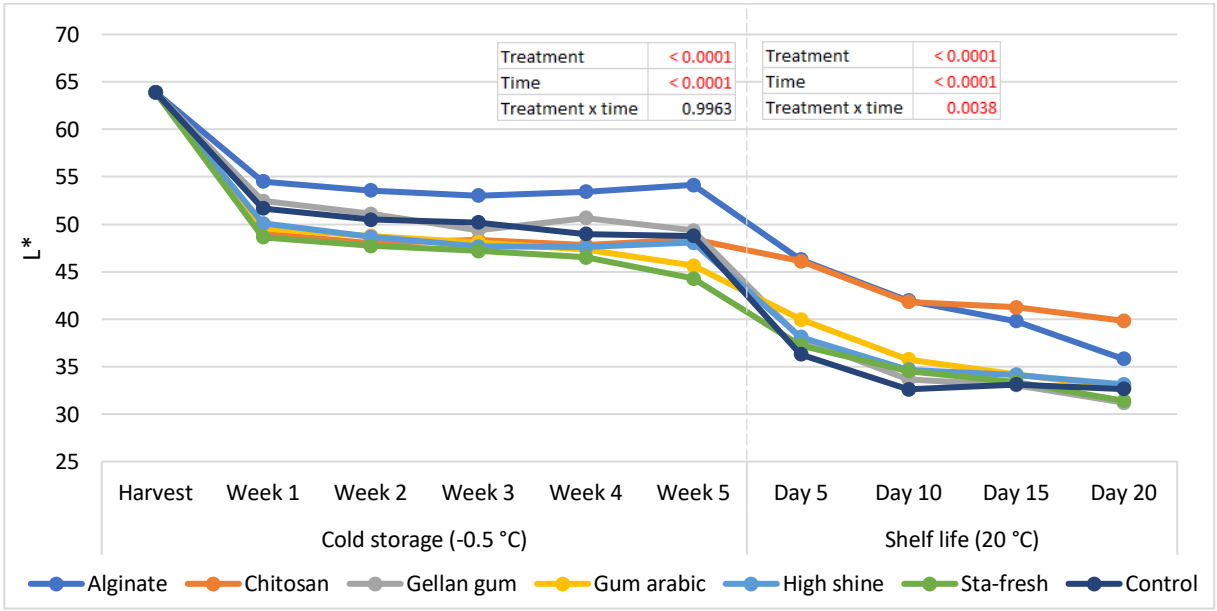

Figure 3. Peel lightness (L*) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

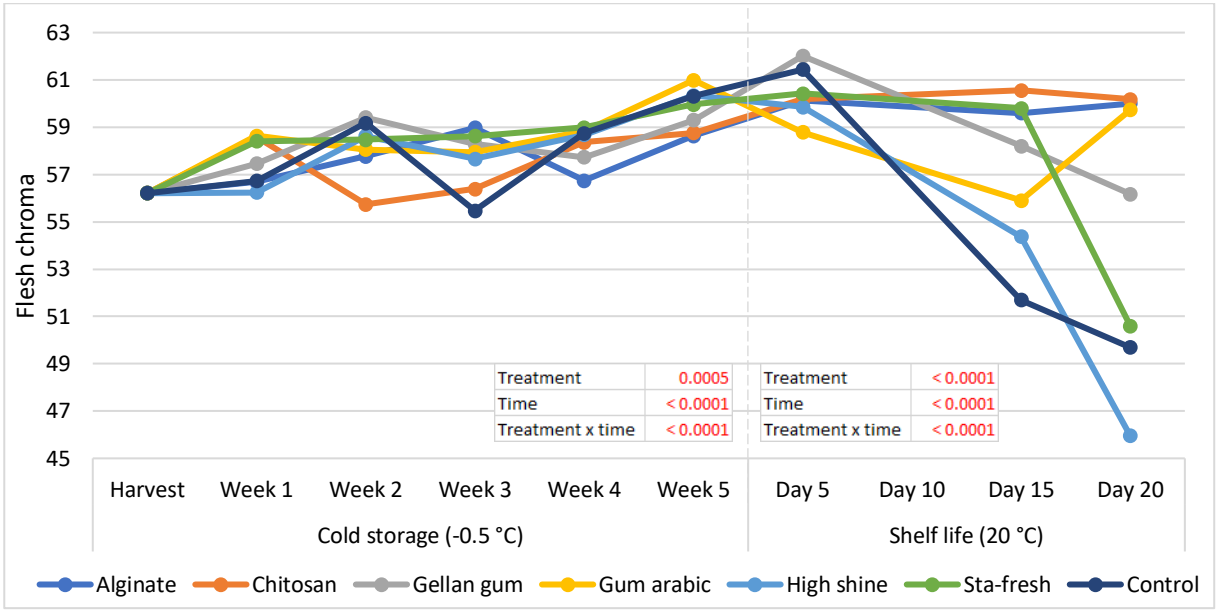

Figure 4. Flesh chroma (C*) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

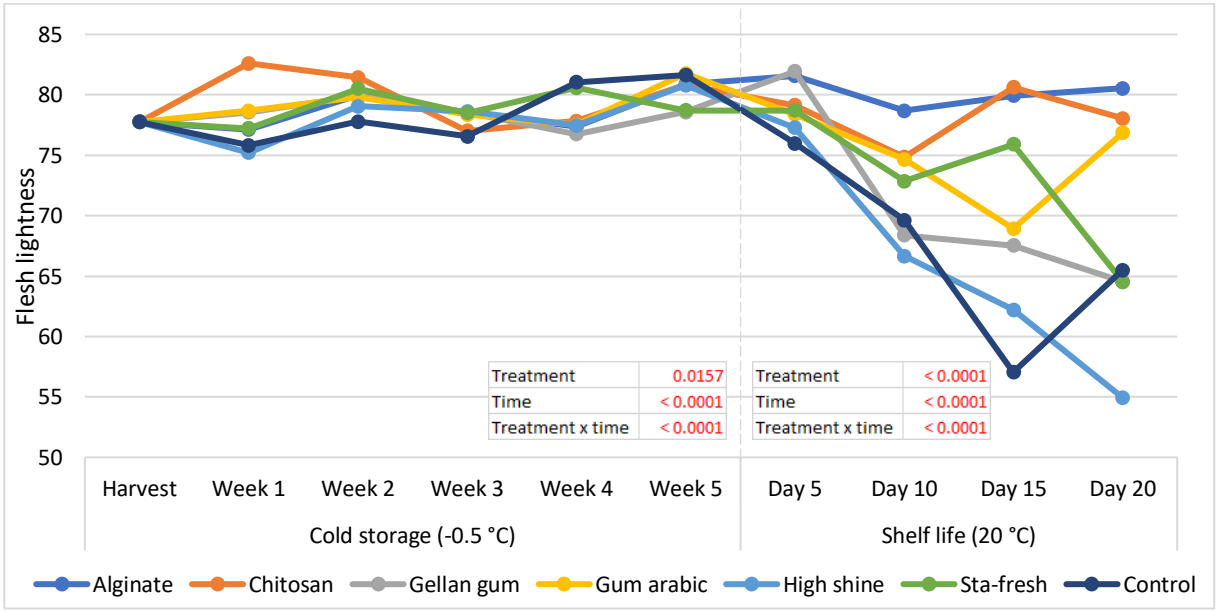

Figure 5. Flesh lightness (L*) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

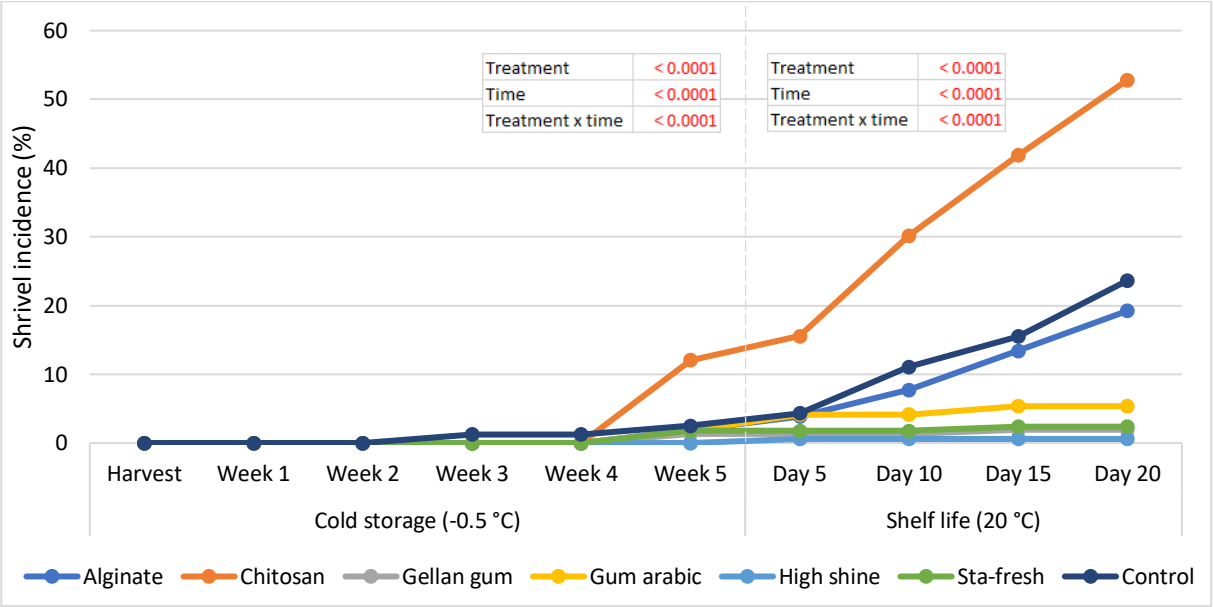

Figure 6. Cumulative shrivel occurrence (%) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

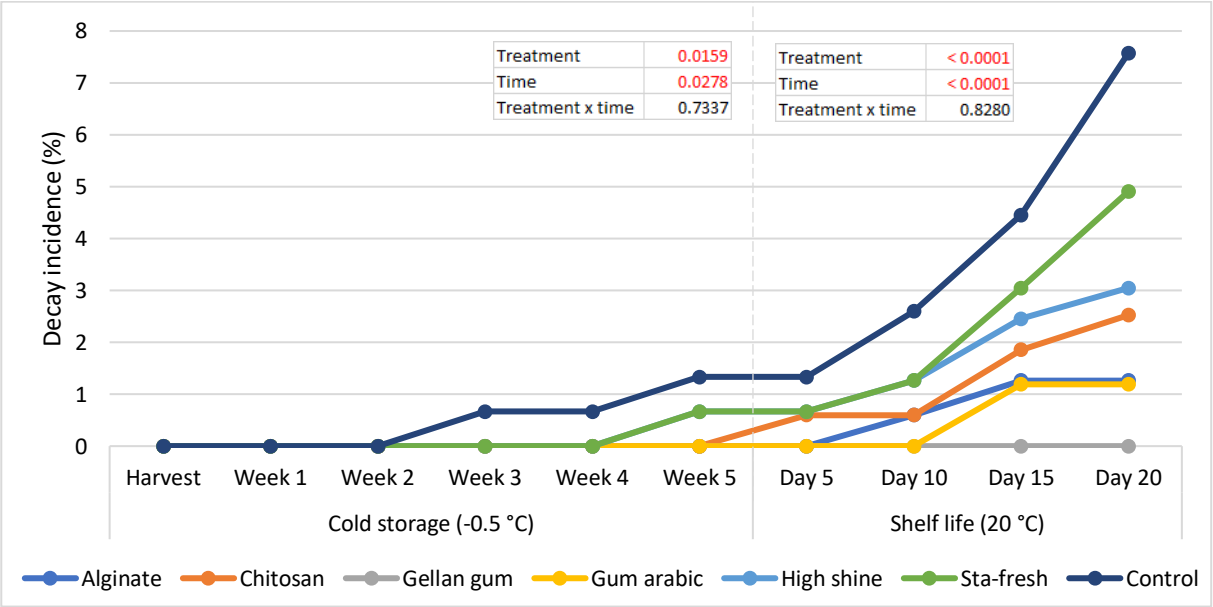

Figure 7. Cumulative decay incidence (%) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 5 weeks) and a subsequent shelf life period (20°C and 80% RH for 20 days). P-values in red are significant.

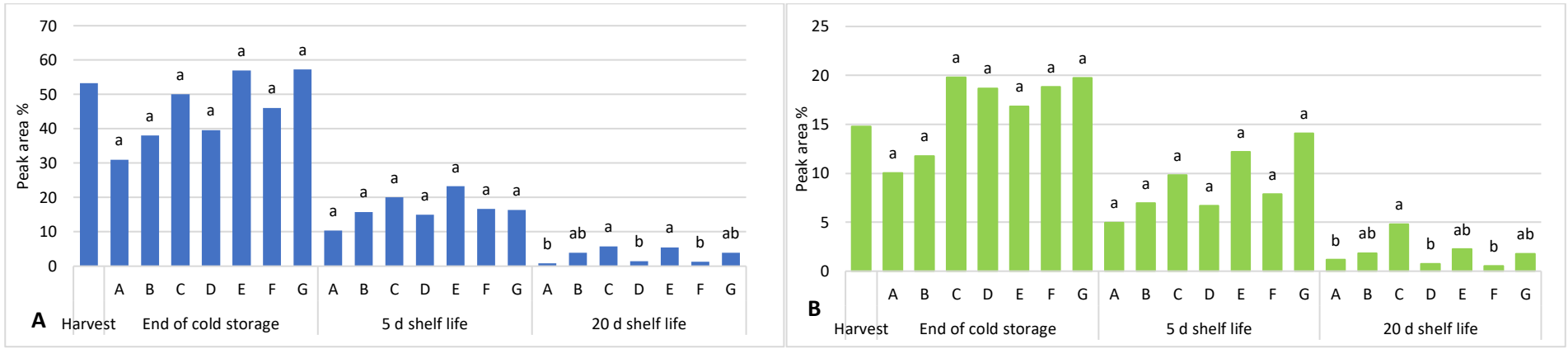

Figure 8. Mean peak area percentage of 1-hexanol (A) and (Z)-3-hexenol (B) in 'African Delight™' plum juice samples at harvest, end of cold storage, 5 d shelf life and 20 d shelf life. Treatment means with different letters within an interval are significantly different ($p<0.05$).

A – alginate, B – chitosan, C – gellan gum, D – gum arabic, E – High shine, F – Sta-fresh, G – control.

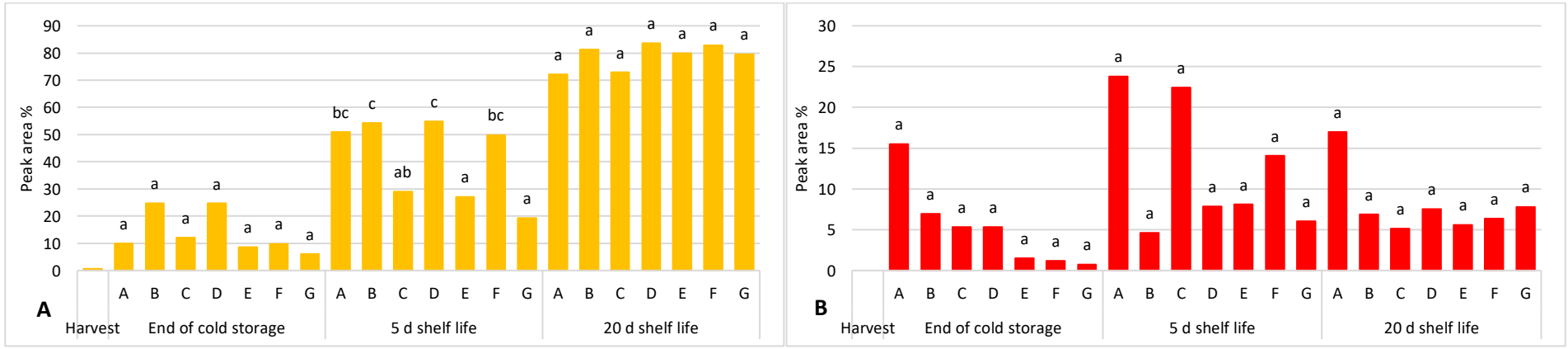

Figure 9. Mean peak area percentage ethanol (A) and ethyl acetate (B) in 'African Delight™' plum juice samples at harvest, end of cold storage, 5 d shelf life and 20 d shelf life. Treatment means with different letters within an interval are significantly different ($p<0.05$).

A – alginate, B – chitosan, C – gellan gum, D – gum arabic, E – High shine, F – Sta-fresh, G – control.

CHAPTER 4: RESEARCH PAPER 2

Effectiveness of gum arabic-based edible coatings on shelf life and quality maintenance in exported plums: assessing commercial viability.

Abstract

Edible coatings are widely reported to reduce postharvest losses in horticultural produce. However, most studies are performed at laboratory-scale where real-life limitations, challenges and postharvest handling practices are not considered. The commercial viability of edible coating application was investigated on 'African Delight™' plums using several gum arabic (GA) based coatings, including GA 2%, GA 5%, GA 10%, GA 5% + pomegranate seed oil and GA 5% + ascorbic acid, applied in a commercial packhouse on a working pack line fitted with an atomizer. Postharvest quality was evaluated during a simulated export regime, including a cold storage shipping period (-0.5 ± 2°C and 90 ± 5% RH for six weeks) and a subsequent shelf life period (20 ± 2°C and 80 ± 5% RH for 15 days). Coatings suppressed respiration and ethylene production, which consequently reduced the rate of fruit ripening. GA 10% performed best, resulting in a significant ($p<0.05$) delay in physico-chemical changes during storage such as fruit softening, loss of acidity and darkening of the peel colour. Descriptive sensory analysis described plums coated with GA 10% as having unripe to semi-ripe sensory attributes at 5 d shelf life, compared to control plums which were characterised with a ripe to overripe sensory profile. This suggests that GA 10% could extend the shelf life of 'African Delight™' plums beyond the current five day end point of commercial sale. No off-flavours were detected in the sensory analysis as a result of coating application. Plums coated with GA 10% were also found to be microbially safe at 5 d shelf life, with no faecal coliforms detected and total coliforms falling within specified limits. Furthermore, coatings exhibited potential as a green replacement technology for HDPE bags. However, the commercial success of edible coating application is limited by the moisture barrier properties of the coatings. All coatings were unsuccessful in significantly reducing weight loss and shrivel development throughout storage, both when fruit were packed with HDPE bags and without HDPE bags. Therefore, future studies should optimise coating moisture barrier properties as well as processing conditions in packhouses to improve coating efficacy, whilst keeping in mind commercial viability.

Keywords: commercial viability, edible coating, gum arabic, plums, quality

1. Introduction

South Africa is the second largest producer of plums in the southern hemisphere, with 74% of plums produced being sold to the export market (HORTGRO, 2018). During export, plums are subjected to a very long handing chain, with shipment periods lasting up to six weeks. Consequently, fruit experience significant quality losses such as moisture loss, shrivelling, overripeness and decay.

Postharvest technologies are heavily relied on to maximise the profitability of exported plums. Low temperature storage (-0.5°C) is implemented during shipment to decrease plum metabolism and delay changes related to ripening (Valero *et al*., 2013). Exported plums are also packaged with high density polyethylene (HDPE) bags to modify the atmosphere within the carton, increasing relative humidity and CO_2 levels in an attempt to reduce respiration and transpiration rates (Pesis *et al*., 2000; Kritzinger *et al*., 2018a). Despite these technologies, quality losses in exported plums are still a major challenge (Kritzinger *et al*., 2018a). In the 2018/2019 season, 18% of plums were rejected upon arrival at the export market due to quality-related issues (P. Roussouw 2019, personal communication, 26 July). Thus, there is a need for an additional postharvest technology to maintain plum quality during export.

Edible coatings have been widely reported as a viable tool to maintain postharvest quality in many different types of fruit, such as banana (Maqbool *et al*., 2011), sweet cherries (Martínez-Romero *et al*., 2006; Mahfoudhi & Hamdi, 2015; Dong & Wang, 2018), guava (Hong *et al*., 2012), table grapes (Meng *et al*., 2008), mango (Baldwin *et al*., 1999), strawberries (Gol *et al*., 2013) and plums (Valero *et al*., 2013; Kumar *et al*., 2017; Thakur *et al*., 2018). Coatings create a semi-permeable protective barrier on the fruit surface that controls moisture, solute and gaseous exchange (Ncama *et al*., 2018). As a result, the rate of ripening may be reduced, which may significantly extend produce shelf life.

Amongst the different types of edible coatings studied in literature, polysaccharide-based composite coatings are highly favoured. These coatings have excellent gas barrier properties and great mechanical properties as a result of a well ordered and tightly packed hydrogen-bonded network structure (Arnon-Rips & Poverenov, 2018), and are widely reported to reduce quality losses. Gum arabic is a hydrocolloid extracted from the stems or branches of *Acacia* species and is Generally Regarded As Safe (FDA, 1999; Andrade *et al*., 2017). It has been reported to significantly delay postharvest quality losses in tomatoes, including reduced weight loss, colour changes, fruit softening, acidity losses and decay incidence (Ali *et al*., 2010). Thus, its application as an edible coating to plums is of interest.

Although there are numerous studies reporting edible coatings to improve postharvest storability and reduce quality losses, few studies consider the commercial viability of the technology.

If coatings were to be applied to fruit on a larger scale where real-life postharvest handling practices and potential temperature abuse were considered, coated fruit may respond differently compared to those treated in a laboratory-scale experiment where conditions are carefully monitored. Furthermore, laboratory-scale experiments typically apply coatings by immersing fruit into the solution for a set time period. However, in commercial packhouses, pack lines are generally equipped with atomizers, which apply postharvest solutions through a spray-action. This spray-action has been reported to deposit less coating onto the fruit's surface compared to when fruit is completely submerged into a coating, resulting in either a thinner barrier being formed (Zhong *et al.*, 2014) or decreased surface coverage (Lerdthanangkul & Krochta, 1996). Therefore, coating efficacy may be reduced.

In addition to maintaining quality, coatings may have the potential to eliminate the need for HDPE bags used to package export plums, by creating a similar modified atmosphere within the individual fruit as that created within the carton by the HDPE bag (Vázquez-Celestino *et al.*, 2016; Ncama *et al.*, 2018). The stigma around plastic packaging and its unsustainability has created an urgent need for a green replacement technology. Edible coatings could fulfil this need; however, to our knowledge, no studies have investigated this potential.

This study investigated the effects of several gum arabic-based composite coatings on the postharvest quality of plums, when coatings were applied in a commercial packhouse to fruit that had been exposed to typical postharvest handling practices. In addition to assessing quality during a simulated shipping period and subsequent shelf life period, a descriptive sensory analysis was conducted to evaluate the influence of edible coatings on the sensory profile of plums. Furthermore, coating sustainability was tested, evaluating the potential of edible coatings to serve as a green replacement technology for the single-use, unsustainable HDPE bags used to package exported plums.

2. Materials and methods

2.1. Edible coatings

Six edible coatings were investigated in this experiment, five of which were gum arabic-based experimental coatings and one a xanthan gum-based, commercial coating registered as Sta-fresh. The following formulations were prepared in the specific order and composition, using distilled water (60°C) to make up the various solutions;

1) Gum arabic (GA, 2% w/v), vegetable oil (1% w/v) and glycerol (1% w/v)
2) Gum arabic (5% w/v), vegetable oil (1% w/v) and glycerol (1% w/v)
3) Gum arabic (10% w/v), vegetable oil (1% w/v) and glycerol (1% w/v)

4) Gum arabic (5% w/v), vegetable oil (0.5% w/v), pomegranate seed oil (PSO, 0.5%) and glycerol (1% w/v)
5) Gum arabic (5% w/v), vegetable oil (1% w/v), glycerol (1% w/v) and ascorbic acid (AA, 0.7% w/v)

Gum arabic, glycerol and ascorbic acid were obtained from Sigma Aldrich, and the pomegranate seed oil and vegetable oil were obtained from Biopurus and a local grocer, respectively. According to the product's application instructions, Sta-fresh (formulation six) was used at 33.3%.

2.2. Commercial-scale coating application, storage and testing

Plum fruit ('African Delight™') were hand-picked at commercial harvest in Tulbagh, Western Cape, South Africa (33.2872 °S, 19.1434 °E). Fruit were held at 10°C for one week, simulating the waiting period that may ensue before fruit are sorted, washed, coated and packed. Fruit homogenous in size were washed on a commercial pack line with ozonated water, and coatings were applied with sprayers in the successive phase of the commercial pack line. Fruit were then automatically dispatched into the packing section and were immediately hand-packed into double layer cartons (39x29x12cm) containing 66 fruit per carton.

Per treatment (1-6), twelve cartons of fruit were packed with high density polyethylene (HDPE) bags, according the industry practice. For the control, 12 cartons of washed, uncoated fruit were packed with HDPE bags. An additional six cartons per treatment (1-5) were packed without HDPE bags and used to assess the potential of edible coatings to eliminate the need for HDPE bags.

After coating, fruit was transported to the laboratory in an air-conditioned vehicle. All fruit were stored at -0.5 ± 2°C and 90 ± 5% relative humidity (RH) for six weeks, simulating shipping conditions, followed by a subsequent 15 day shelf life period at 20 ± 2°C and 80 ± 5% RH, where the cartons were opened, and HDPE bags were removed. This long shelf life period was extended past the commercial sale end point of shelf life (5 days) in order to evaluate the shelf life extension potential of the coatings. Temperature and relative humidity were monitored throughout storage using a data logger (Tinytag TV-4500, Gemini Data Loggers, UK).

Instrumental quality tests were conducted at harvest, at bi-weekly intervals during cold storage and at five day intervals during shelf life using 20 randomly selected fruit from four cartons per treatment for each sampling date. A full instrumental analysis was conducted at each interval for plums packed with HDPE bags. For plums packed without HDPE bags, flesh firmness, peel colour parameters, weight loss and shrivel incidence were assessed at the end of the cold storage period.

2.3. Physiological responses

2.3.1. Respiration rate

Fruit respiration rate was measured as the amount of CO_2 evolved by fruit using the closed system method as described by Fawole and Opara (2013a), with slight modification. Three randomly selected plums were placed in a 1 L hermetically sealed glass jar for 1 h with a lid containing a rubber septum. After incubation, CO_2 production inside each glass jar was measured from the head space through the rubber septum using an O_2/CO_2 gas analyser (Checkmate 3, PBI Dansensor, Denmark). All measurements were taken in triplicate. Results were presented as the mean ± S.E (mL CO_2/kg.h) of determinations obtained (n = 3) per treatment for each interval.

2.3.2. Ethylene production

Ethylene production was measured using the closed system method, as described by Fawole and Opara (2013a), with slight modification. Three randomly selected plums were placed in a 1 L hermetically sealed glass jar for 1 h with a lid containing a rubber septum. After incubation, ethylene production was measured from the head space through the rubber septum using an ICA56 Ethylene Analyzer (Fricaval 89, Spain). All measurements were taken in triplicate. Results were presented as the mean ± S.E. (µL C_2H_4/kg.h) of determinations obtained (n = 3) per treatment for each interval.

2.4. Physico-textural properties

2.4.1. Colour attributes

Fruit colour was assessed in the CIELAB coordinates (L*, a*, b*) using a Minolta Chroma Meter CR-400 (Minolta Corp, Osaka, Japan) after calibration with a white tile background (Fawole & Opara, 2013a). Two measurements were on opposite sides of the equatorial region of individual plums (Fig. 1, Appendix). Changes in peel colour were recorded over storage using a constant 15 fruit per treatment, with markings indicating the area for measurement. Fruit flesh colour was assessed using 10 randomly fruit per treatment that were peeled with a vegetable peeler. Colour changes were reported using lightness (L*) ranging between L* = 0 (black) and L* = 100 (white). In addition, hue angle (*h*°) was calculated according to equation (1) where 0°=red-purple, 90°=yellow, 180°=blue-green, and 270°=blue (1). Results were expressed as mean ± S.E. of determinations obtained (n = 20) per treatment for each interval.

Hue angle = arctangent (b*/a*) (1)

where a* = redness (positive) to greenness (negative) and b* = yellowness (positive) to blueness (negative)

2.4.2. Flesh firmness

Flesh firmness was determined according to the method described by Fawole and Opara (2013a), with modification. Using a firmness analyser (GÜSS-FTA, South Africa) fitted with an 11 mm diameter cylindrical probe and programmed to penetrate 14.5 mm into the test fruit at speed of 10 mm/s, flesh firmness was measured at each interval using 10 randomly selected plums per treatment. Tests were performed in duplicate on fruit peeled with a vegetable peeler on opposite sides of the equatorial region (Fig. 1, Appendix). Peak force (N) required to penetrate plum flesh was taken as flesh firmness. Results were expressed as mean ± S.E. of determinations obtained (n = 20) per treatment for each interval.

2.5. Chemical properties

2.5.1. Total Soluble Solids

Total soluble solids (TSS, °Brix) was determined using a digital refractometer (Palette, PR-32 ATAGO, Bellevue, USA) calibrated with distilled water. Pooled juice samples of two fruit per replicate, with five replicates per treatment, were measured. TSS (°Brix) values were reported as the mean ± S.E. of determinations obtained (n = 5) per treatment for each interval (Fawole & Opara, 2013b).

2.5.2. Titratable Acidity

Titratable acidity (TA, %) was determined using an automated titrator (Metrohm AG 760, Herisau, Switzerland) according to the method described by Fawole and Opara (2013b). Pooled juice samples of two fruit per replicate, with five replicates per treatment, were measured. TA was expressed as the percentage of malic acid (%MA) and reported as the mean ± S.E. of determinations obtained (n = 5) per treatment for each interval.

2.5.3. TSS/TA and BrimA

TSS/TA and BrimA were calculated from the TSS and TA values obtained per treatment for each interval. BrimA was calculated according to equation (2).

$$BrimA = TSS - k*TA \quad (2)$$

where TSS = total soluble solids (°Brix), TA = titratable acidity (%MA) and k is the tongue's sensitivity index ranging between 2 - 10 (Fawole & Opara, 2013b), where a k-value of five was used. Results were expressed as mean ± S.E. of determinations obtained (n = 5) per treatment for each interval.

2.6. Physiological disorders

2.6.1. Weight loss

Fifteen constant fruit per treatment were weighed individually at each interval throughout storage using an electronic scale (Mettler, Toledo, Switzerland, 0.0001 g accuracy). The weight loss of each fruit was calculated according to equation (3) and reported as the mean ± S.E. of determinations obtained (n=10) per treatment for each interval (Mphahlele *et al*., 2016).

$$\text{Weight loss (\%)} = [(W_i - W_t) \div W_i] \times 100 \quad (3)$$

where W_i is the weight (g) of the fruit at harvest and W_t is the weight (g) of the fruit at the storage interval.

2.6.2. Shrivel and decay incidence

Shrivel incidence was assessed using a constant three cartons of fruit (50 plums per carton) and calculated according to equation (4). A plum was deemed shrivelled when the shrivel extended halfway or more over the shoulder of the fruit, as classified by packhouse management (Fig. 2, Appendix). The cumulative mean (%) ± S.E. was reported per treatment for each interval (Kritzinger *et al*., 2018b).

$$\text{Shrivel incidence (\%)} = \frac{shrivelled\ fruit\ in\ carton}{total\ fruit\ in\ carton} \times 100 \quad (4)$$

Decay incidence was assessed using a constant three cartons of fruit (50 plums per carton) and calculated according to equation (5). The cumulative mean (%) ± S.E. was reported per treatment for each interval (Ali *et al*., 2010).

$$\text{Decay incidence (\%)} = \frac{decayed\ fruit\ in\ carton}{total\ fruit\ in\ carton} \times 100 \quad (5)$$

2.7. Evaluation of microbial safety

To assess the microbial quality of the plum samples before conducting a sensory analysis, plums coated with GA 10% and Sta-fresh, as well as control plums were tested for total plate count, total coliforms and faecal coliforms at 5 d shelf life (Sureshkumar *et al*., 2016; Munhuweyi *et al*., 2017). Per treatment, three replicates of five plums each (unwashed) were used. Using a knife, the peel of the plum samples was removed with approximately 1 cm of flesh intact and cut into smaller fragments. Ten grams of each replicate was added to 40 mL physiological salt solution and blended.

A dilution series was plated in triplicate onto total plate count agar (Lab M, UK) to assess aerobic mesophilic bacteria, and MacConkey media (Biolab, Merck, USA) to assess total coliforms and faecal coliforms. The plates were incubated at 37°C for 48 h, after which the plates with a range of 30-300 colonies were counted. Results were expressed as the mean log CFU/g fresh plum per test ± S.E.

2.8. Descriptive sensory analysis

A sensory analysis was performed at 5 d shelf life on control plums, plums coated with Sta-fresh and plums coated with GA 10% to compare the sensory profiles of the three treatments. All plum samples used in the sensory analysis were packed with HDPE bags during the cold storage period that preceded shelf life.

2.8.1. Training of sensory panel

The panel consisted of twelve female panellists with previous formal sensory evaluation experience. During six sessions, training of the panel was conducted using reference samples to create a new, uniform frame of reference for the meaning of specific attributes, in addition to calibrating the panellists on the intensities for such attributes using a 100-point line scale (Lawless & Heymann, 2010). A combination of ballot and consensus training was used to develop a baseline score sheet of associated sensory attributes identified in plum fruit (Table 2, Appendix),

2.8.2. Sensory testing of treatments

Eight replications per treatment were tested, with each replication testing plums from an individual carton. Attributes were scored during eight 30 min blind-tasting sessions, with one replication analysed per session. These sessions took place over three days, with three replications analysed on the first two days and two on the final testing day. All sensory assessments were conducted at ambient room temperature (21°C) and in controlled lighting, in individual testing booths in the Sensory Laboratory, Food Science Department, Stellenbosch University, South Africa. Panellists were provided with mineral water and unsalted, fat-free biscuits to cleanse their palates between samples. Plum fruit were washed, and then cut along the suture line and twisted to separate. Two halves were served in glasses enclosed by clean Petri dishes, to create aroma headspace. The three samples were coded with three-digit random numbers and the serving order was randomised per panellist. Sensory ratings were recorded using the Compusense five sensory data acquisition program (Guelph, Ontario, Canada).

In order to explore the relationships between sensory and instrumental quality attributes, corresponding replications of plums used for the sensory analysis were also used for instrumental

measurements including peel and flesh colour parameters, flesh firmness, titratable acidity, total soluble solids, TSS/TA and BrimA.

2.9. Statistical analysis

Instrumental data was analysed with Statistica software package 13.3 (Tibco Software Inc.). A one-way analysis of variance (ANOVA) was performed, with the various treatments providing sources of variation. ANOVA-generated P-values and significant differences between means were determined using Duncan's multiple range test, with a 95% confidence interval. A factorial ANOVA was also performed to calculate the interaction of the main factors: treatment and storage.

Sensory data was pre-processed for application in multivariate analyses. Panel performance was monitored using Panel Check Software (Version 1.4.1, www.panelcheck.com). In the event of significant non-normality ($p<0.05$), outliers were identified and removed (Fawole & Opara, 2013b). A one-way analysis of variance (ANOVA) was performed on the various treatments using Statistica software package 13.3 (Tibco Software Inc., California, USA). ANOVA-generated P-values and significant differences between means were determined using Duncan's multiple range test, with a 95% confidence interval. Correlation coefficients (r) were determined by the Pearson correlation matrix method using XLStat, version 7.5.2 (Addinsoft, New York, USA). Additionally, linear regressions and principal component analysis (PCA) were performed using XLStat, version 7.5.2 (Addinsoft, New York, USA).

3. Results and discussion

3.1. Physiological response

3.1.1. Respiration rate

From harvest (21.38 mL/kg.h), respiration rate increased in all treatments throughout cold storage (Fig. 1), with levels being highest at two weeks cold storage in control plums (44.15 mL/kg.h) and plums coated with GA 2% (50.11 mL/kg.h) and GA 5% + AA (40.08 mL/kg.h). This high respiration rate may have been a result of fruit stress, due to the changing temperature of the surrounding environment when fruit were moved from harvest (ambient temperature) conditions to cold storage (-0.5°C, 90% RH) conditions (Bron *et al*., 2005). However, respiration in plums coated with GA 5% (33.70 mL/kg.h), GA 10% (33.23 mL/kg.h), GA 5% + PSO (36.95 mL/kg.h) and Sta-fresh (38.16 mL/kg.h) was significantly ($p<0.05$) lower at two weeks cold storage compared to control plums. Although not clear, these coatings may have maintained a more stable environment within the fruit throughout the temperature change, preventing a sharp increase in respiration rate.

At the end of cold storage, respiration rate did not differ significantly ($p \geq 0.05$) between control plums (30.47 mL/kg.h) and coated plums (32.94 - 36.59 mL/kg.h), except for plums coated with GA 5% + PSO (43.92 mL/kg.h) and Sta-fresh (41.20 mL/kg.h). At 5 d shelf life, respiration rate in control plums was observed to peak (48.10 mL/kg.h). In coated plums, however, this peak in respiration rate was delayed until 10 d shelf life and reduced (41.91 - 46.85 mL/kg.h). Climacteric fruit exhibit a peak in respiration rate at the onset of senescence (Maftoonazad *et al.*, 2008). Therefore, ripening may have been delayed in coated fruit, consequently delaying the onset of senescence and extending shelf life.

Our findings are in agreement with that of Bal (2013) and Kumar *et al.* (2017), who reported a delayed climacteric peak in coated fruit compared to control fruit. Coating gas barrier properties may have limited oxygen intake by sealing lenticels and covering the epicarp, resulting in a suppressed respiration rate and thus, reduced ripening (Maqbool *et al.*, 2011; Díaz-Mula *et al.*, 2012; Kumar *et al.*, 2017; Xin *et al.*, 2017).

3.1.2. Ethylene evolution

Ethylene production increased from 0.25 µL/kg.h at harvest, to between 0.60 (GA 2%) and 2.57 µL/kg.h (GA 5% + AA) at the end of cold storage (Fig. 1). During cold storage, there was no significant difference ($p \geq 0.05$) in ethylene production between treatments, except for plums coated with GA 5% + AA at the end of cold storage.

When fruit were moved to shelf life conditions, however, ethylene production increased significantly. Higher storage temperatures have been reported to increase the activity of enzymes responsible for ethylene production such as 1-aminocyclopropane-1-carboxylic acid (ACC) synthase and oxidase, which consequently accelerates the rate of ripening (Valero *et al.*, 2013; Thakur *et al.*, 2018; Zhao *et al.*, 2018). However, coated plums maintained a lower ethylene production at 5 d shelf life compared to control plums (8.33 µL/kg.h), with the effect being significant ($p<0.05$) in plums coated with GA 2% (3.66 µL/kg.h), GA 5% (2.89 µL/kg.h) and GA 5% + PSO (3.76 µL/kg.h). Coatings may have reduced ripening as a result of suppressed respiration, which could have lowered ethylene production (Valero *et al.*, 2013). Similar results have been reported by Mahfoudhi and Hamdi (2015) in gum arabic coated sweet cherries.

At 15 days shelf life, ethylene production was high in all treatments (16.10 - 26.77 µL/kg.h), which could a result of senesce.

3.2. Physico-textural attributes

3.2.1. Colour attributes

3.2.1.1. Peel colour

The peels of 'African Delight™' plums at harvest were a bright red-yellow colour, corresponding to a lightness (L*) of 48.36 and a hue angle (*h*°) of 33.46. During cold storage, peel colour was maintained in all treatments. Lightness (45.38) and hue angle (27.87) in control fruit did not differ significantly ($p \geq 0.05$) from coated fruit at the end of cold storage (Table 1).

During shelf life, plum peels darkened and turned a deep red-purple shade, corresponding to a decline in lightness and hue angle. However, plums coated with GA 10% maintained a significantly ($p < 0.05$) higher L* value (36.96) and *h*° (14.89) compared to control plums (L* = 34.36; *h*° = 9.48) at 5 d shelf life. Similarly, lightness and hue angle were significantly ($p < 0.05$) higher in plums coated with GA 10% (L* = 34.67; *h*° = 6.37) compared to control (L* = 32.23; *h*° = 2.15) plums at 15 d shelf life, indicating a retention of unripe peel colour throughout storage.

In red-purple plum cultivars such as 'African Delight™', peel colour changes occur during ripening as a result of anthocyanin synthesis (Díaz-Mula *et al*., 2009; Liu *et al*., 2014; Kumar *et al*., 2017). In plums coated with GA 10%, the synthesis of these red compounds may have been reduced as a result of suppressed respiration, consequently delaying colour changes in the peel during ripening (Tucker, 1993; Liu *et al.*, 2014).

Similar results have been reported in gum arabic coated cherries stored at 2°C and 90-95% RH for 15 days. The author reported coated cherries to maintain their bright red colour throughout storage, whilst control cherries became more red and darker, corresponding to a decrease in hue angle (Mahfoudhi & Hamdi, 2015).

3.2.1.2. Flesh colour

At harvest, plum flesh colour was a light yellow shade that corresponding to a lightness of 85.46 and a hue angle of 85.67 (Table 2). Flesh lightness was maintained throughout cold storage (84.82 - 88.38 at six weeks), except for plums coated with GA 2% (72.06). Hue angle decreased slightly during cold storage as plum flesh became somewhat more orange. However, plums coated with GA 10% had a significantly ($p < 0.05$) higher flesh hue angle (84.35) than control plums (80.44) at the end of cold storage, indicating a better retention of flesh colour.

During shelf life, lightness and hue angle decreased as flesh colour darkened and became more orange. However, colour changes were delayed in coated plums. At 15 d shelf life, lightness and hue angle were significantly ($p < 0.05$) higher in plums coated with GA 2% (L* = 79.66 and *h*° = 65.43), GA 10% (L* = 80.74 and *h*° = 67.47), GA 5% + PSO (L* = 82.78 and *h*° = 65.72) and GA 5% + AA

(L* = 86.09 and *h*° = 76.75) compared to control plums (L* = 64.04 and *h*° = 54.89). Carotenoids are orange pigments that are synthesized in the flesh of plums during ripening. The higher hue angles observed in coated fruit could be linked to reduced carotenoid synthesis as a result of suppressed respiration (Valero *et al.*, 2013; Martínez-Romero *et al*., 2017).

3.2.2. Flesh firmness

Flesh firmness was maintained from harvest (41.48 N) throughout cold storage (Fig. 2). No significant difference ($p \geq 0.05$) in flesh firmness was observed between control (41.52 N) and coated plums at the end of cold storage, except for plums coated with GA 2% (33.49 N) and Sta-fresh (33.78 N).

When plums were moved to shelf life conditions (20°C, 80% RH), flesh firmness decreased rapidly. However, plums coated with GA 10% (22.18 N), GA 5% + PSO (25.12 N), GA 5% + AA (29.18 N) and Sta-fresh (27.90 N) had a significantly ($p<0.05$) higher flesh firmness compared to control fruit (12.31) at 5 d shelf life. Furthermore, plums coated with GA 10% maintained a significantly ($p<0.05$) higher flesh firmness throughout shelf life (18.68 N at 10 d and 14.04 N at 15 d) compared to control plums, which had a flesh firmness of 7.06 N and 6.03 N at 10 d and 15 d shelf life, respectively.

During ripening, fruit softening occurs as cell wall hydrolysing enzymes such as β-galactosidase, polygalacturonase, 1,4- β-D-glucanase/glucosidase and pectin methylesterase reduce cell-to-cell adhesion and cell wall mechanical strength (Maftoonazad *et al.*, 2008; Valero *et al.*, 2013). At shelf life temperatures (20°C), the activity of these enzymes increases as a result of increased respiration (Zhao *et al.*, 2018). However, coatings may have reduced enzymatic activity by suppressing respiration, resulting in a better maintenance of flesh firmness throughout shelf life (Liu *et al.*, 2014; Kumar *et al.*, 2017). Similar results have been reported in gum arabic-coated tomatoes stored at 20°C and 80–90% RH for 20 days (Ali *et al.*, 2010) and gum arabic-coated cherries stored at 2°C and 90-95% RH for 15 days (Mahfoudhi & Hamdi, 2015).

3.3. Chemical attributes

3.3.1. Total soluble solids

From harvest (17.28 °Brix), total soluble solids (TSS) was maintained throughout cold storage (Table 3), with neither treatment nor time observed to have a significant effect ($p \geq 0.05$) on TSS. At 5 d shelf life, TSS was maintained (16.30 °Brix – 17.88 °Brix), with no significant difference ($p \geq 0.05$) observed between treatments. However, TSS in control plums increased at 10 d shelf life (18.84 °Brix). All coated plums maintained lower TSS than control plums at 10 and 15 d shelf life, except for plums coated with Sta-fresh at 10 d shelf life (18.94 °Brix).

TSS increases during ripening as starch is hydrolysed into simple sugars by catabolic processes (Kumar *et al.*, 2017). The low TSS observed in coated fruit during shelf life could be linked to reduce ripening as a result of suppressed respiration. A similar effect was observed in gum arabic coated sweet cherries stored at 2°C and 90-95% RH for 15 days (Mahfoudhi & Hamdi, 2015) and chitosan coated plums stored at 5 ± 1°C and 90 ± 5% RH for 20 days (Liu *et al.*, 2014).

3.3.2. Titratable acidity

Titratable acidity (TA) declined steadily over storage, measuring 0.95% at harvest, between 0.67% and 0.84% at the end of cold storage and between 0.39% and 0.47% at the end of shelf life (Table 3). Organic acids within the fruit are used as primary substrates in metabolic processes during ripening, resulting in a reduction in TA (Valero *et al.*, 2013). At the end of cold storage, TA was significantly ($p<0.05$) higher in fruit coated with GA 5% (0.84%) and GA 10% (0.83%) compared to control fruit (0.67%). Acid metabolic activities could have been suppressed in coated fruit compared to control fruit during cold storage as a result of reduced respiration. Similar results have been reported in gum arabic coated sweet cherries stored at 2°C and 90-95% RH for 15 days (Mahfoudhi & Hamdi, 2015). In shelf life, treatments were not found to have a significant effect on TA ($p\geq0.05$).

3.3.3. TSS/TA and BrimA

BrimA increased slightly during cold storage, from 12.55 at harvest to between 12.85 and 13.45 at the end of cold storage (Table 4). Treatments were not observed to have a significant effect on BrimA in cold storage ($p\geq0.05$). TSS/TA also increased during cold storage, from 17.28 at harvest to 25.48 in control plums at the end of cold storage. However, TSS/TA in plums coated with GA 5% (20.71) and GA 10% (20.50) was significantly ($p<0.05$) lower than in control plums at the end of cold storage (Table 4).

In shelf life, TSS/TA and BrimA continued to increase. However, TSS/TA in plums coated with GA 10% (23.19) was significantly ($p<0.05$) lower compared to control plums (32.16) at 5 d shelf life. At 15 d shelf life, there was no significant difference in TSS/TA ($p\geq0.05$) between treatments. Conversely, BrimA did not differ significantly ($p\geq0.05$) between treatments at 5 d shelf life, but by 15 d shelf life, BrimA was significantly ($p<0.05$) lower in plums coated with GA 5% (13.31) and GA 10% (13.62) compared to control plums (15.71).

TSS gives an indication of fruit maturity, therefore, the low TSS/TA in coated fruit compared to control fruit could be linked to reduced ripening as a result of suppressed respiration. At the end of shelf life, however, fruit maturity may have been similar between treatments. BrimA has been reported as a more accurate indication of fruit flavour compared to TSS/TA (Tietel *et al.*, 2011),

measuring the balance between sweetness and sourness using a constant (k) that reflects the tongue's higher sensitivity to TA compared to TSS (Magwaza & Opara, 2015). The delayed increase in BrimA in coated plums towards the end of shelf life may indicate that coatings slowed the rate of flavour development in fruit as a result of suppressed respiration. To our knowledge, this is the first time that BrimA has been reported in coated fruit compared to control fruit.

3.4. Physiological disorders

3.4.1. Weight loss

Moisture loss accounts for 97% of the total weight loss experienced by fruit (Díaz-Pérez *et al.*, 2007). Therefore, weight loss can be used as a measure of moisture loss in plums. Weight loss was not accounted for from harvest until the end of the holding period (1 week at 10°C). Significant moisture loss may have occurred in this period, before fruit were coated. Chigwaya *et al*. (2016) observed weight loss to be significantly higher in 'August Red' nectarines held at 20°C for 48 h (3.8%) compared to fruit that were packed within 12 h of harvest (1%).

During cold storage and shelf life, weight loss was significantly ($p<0.05$) influenced by both treatment and time, however, there was no significant interaction ($p\geq0.05$) between these two factors (Fig. 3). At the end of the cold storage period, plums coated with GA 2% (0.72%), GA 5% (0.32%), GA 5% + PSO (0.87%) and GA 5% + AA (0.68%) had experienced less weight loss than control plums (0.88%), however, the effect was not significant ($p\geq0.05$).

When plums were moved to shelf life conditions (20°C and 80% RH), weight loss increased significantly ($p<0.05$) in all treatments. Weight loss was generally lower in coated plums compared to control plums throughout shelf life, however, the effect was not significant ($p\geq0.05$) except for plums coated with GA 2% at 5 d shelf life.

Edible coatings have been widely reported to create a physical barrier to moisture loss, resulting in a significant reduction in weight loss throughout storage (Ali *et al.*, 2010; Valero *et al.*, 2013; Liu *et al.*, 2014; Kumar *et al.*, 2017). However, the ability of coatings to reduce weight loss was limited in this study, as no significant difference ($p\geq0.05$) was observed between coated and control plums at the end of cold storage or at the end of shelf life. This contradicts the findings of other authors, whereby weight loss was significantly reduced in gum arabic coated cherries stored at 2°C and 90–95% RH for 15 days (Mahfoudhi & Hamdi, 2015) and gum arabic coated tomatoes stored at 20°C and 80–90% RH for 20 days (Ali *et al.*, 2010). However, these studies were performed at laboratory-scale; therefore, fruit may have responded differently compared to this study, whereby coatings were applied at commercial scale, and fruit were exposed to real-life postharvest handling practices.

In a laboratory-based experiment, a small volume of fruit is usually treated. Fruit tend to be harvested and immediately transported back to the laboratory to be processed. Furthermore, coatings are applied by immersing fruit into the solution for a set time period, and thereafter, fruit are left to completely dry before packing. In our experiment, the increased fruit volume, additional holding period before coating application (1 week at 10°C), use of atomizers to apply coatings by a spray-action, and reduced drying time before packing may have decreased the efficacy of the coatings, resulting in increased moisture loss. Spray-applications have been reported to deposit less coating onto the product's surface in comparison to dipping, resulting in a thinner barrier being formed (Zhong *et al*., 2014), or result in incomplete surface coverage (Lerdthanangkul & Krochta, 1996).

3.4.2. Shrivel incidence

Regardless of treatment, shrivel incidence increased throughout storage (Fig. 4). Although shrivel incidence was lower in plums coated with GA 10% (7.58% at 5 d and 9.09% at 15 d shelf life) and Sta-fresh (3.54% at end of cold storage and 6.57% at 5 d shelf life) compared to the control (5.56%, 9.09% and 12.63% at end of cold storage, 5 d and 15 d shelf life, respectively), the effect was not significant ($p \geq 0.05$). No coating was observed to significantly control shrivel development throughout storage.

As plums lose moisture, there is a loss of turgor in the epidermal cells, resulting in an overall reduction in fruit volume (Kritzinger *et al.*, 2018a). A shrivelled appearance results because the fruit cuticle has limited elasticity and maintains its surface area. In this study, a regression of weight loss by shrivel indicated a strong positive relationship between the two factors ($R^2 = 0.710$; $r = 0.843$), similar to that described by Vázquez-Celestino *et al*. (2016). Therefore, the non-significant effect of coatings on shrivel incidence can be associated with the inability of the coatings to significantly reduce weight loss, and thus moisture loss throughout postharvest storage.

Edible coatings have been reported to reduce shrivel incidence in literature, with Chaple *et al.* (2017) reporting methyl cellulose coated chillies to be free from shrivelling, while control chillies show moderate to severe symptoms. However, this study was performed at laboratory-scale, by immersing the chillies into the coating solution and leaving them to surface dry before being stored. In this study, fruit were treated on a commercial scale, whereby real-life postharvest handling practices were considered. This may have affected the ability of the coatings to control shrivel development. Major moisture loss could have occurred in the holding period (1 week at 10°C) before fruit were coated, nullifying the coating's effect on shrivel control. Furthermore, coating barrier properties may have been reduced as a result of the spray-application on pack lines. Spraying has

been reported to resulted in reduced surface coverage compared to that achieved with dipping which is commonly used in laboratory-scale trials (Lerdthanangkul & Krochta, 1996; Zhong *et al.*, 2014).

3.4.3. Decay incidence

No decay was observed at the end of cold storage, however, decay incidence increased when fruit was moved into shelf life conditions (20°C and 80% RH). In contrast to cold storage conditions, shelf life conditions favour microorganism growth (Zagory, 1999). Coatings were not found to accelerate decay throughout storage compared to the control. All coated plums had a lower decay incidence at 15 d shelf life (3.03% - 9.09%) compared to control plums (11.11%); however, the effect was not significant ($p \geq 0.05$) except for plums coated with GA 2% (Fig. 5).

In a study on peaches stored at 10°C and 85-90% RH for 32 days, decay incidence was reported to be significantly lower in fruit coated with 1% gum arabic compared to control fruit (Asghar *et al.*, 2014). However, this study was performed at laboratory-scale; therefore, our findings may not be comparable. Coating application in a commercial environment may have reduced the antimicrobial potential of gum arabic.

3.5. Microbial evaluation

At 5 d shelf life, aerobic mesophilic bacteria were counted as 4.31 log CFU/g in control plums. In plums coated with GA 10% and Sta-fresh, microbial loads were lower than control plums (3.10 log CFU/g and 3.50 log CFU/g, respectively), with the effect being significant ($p<0.05$) in plums coated with GA 10% (Table 5). According to the Australia New Zealand Food Standards Code, fresh fruit are specified as a Category 4 Ready-To-Eat (RTE) food; therefore, standard plate count limits are not considered applicable. This is because fruit have a natural microbial flora that does not usually present a risk to human health, with total microbial populations reported to range between 4 and 6 log CFU/g (Pao & Brown, 1998). Regardless, it was important to confirm that coating application did not contribute to an increased aerobic mesophilic bacteria count in plums.

Coliform bacteria such as *Klebsiella* and *Enterobacter* frequently occur in fresh produce, originating from the soil, or from postharvest handling practices (Pao & Brown, 1998). At 5 d shelf life, total coliforms were counted as 3.02 and 3.03 log CFU/g in plums coated with GA 10% and Sta-fresh, respectively, whilst total coliforms were counted as less than 1 log CFU/g in control plums. The increased total coliform count in coated fruit may have been a result of increased postharvest handling through the additional coating step that was implemented in the packhouse. Regardless, all treatments fell within the range specified by the Australia New Zealand Food Standards Code (2-4 log CFU/g RTE food).

E. coli is a faecal coliform that may cause human illness. The Australia New Zealand Food Standards Code identifies a satisfactory limit of <3 CFU/g in Ready-To-Eat foods. No faecal coliforms were detected in any of the treatments at 5 d shelf life, validating the microbial safety of the plums for consumption in a descriptive sensory analysis.

3.6. Sensory analysis

Descriptive sensory analysis was conducted to determine the influence of edible coatings on the sensory profiles of plums (Fig. 6). At 5 d shelf life, plums coated with GA 10% scored significantly ($p<0.05$) higher than control plums and plums coated with Sta-fresh in attributes describing the profile of an unripe to semi-ripe plum, such as green aroma (21.13), unripe flavour (22.14), sour taste (39.26) and firm texture (58.79). Therefore, the rate of ripening in plums coated with GA 10% may have been reduced compared to the other two treatments. Similar results were reported in tomatoes coated with guar gum (Ruelas-Chacon *et al*., 2017). In plums coated with Sta-fresh, no significant difference ($p\geq0.05$) in plum aroma, peel and flesh appearance, and overripe flavour was observed compared to control plums. However, plums coated with GA 10% scored significantly ($p<0.05$) lower in these attributes. Therefore, Sta-fresh may not have been as effective as GA 10% in reducing ripening, with Sta-fresh coated plums exhibiting similar sensory attributes to control plums at 5 d shelf life.

A principal component analysis (PCA) of the sensory results and the corresponding instrumental results in the three treatments shows a similar trend (Fig. 7). The biplot shows 100% of the total variation in the data set, with 86.10% of variation shown by F1 and 13.90% shown by F2. On the positive side of F1, control plums and plums coated with Sta-fresh associate with attributes describing the profile of a ripe to overripe plum (plum aroma, plum flavour, overripe flavour, sweetness, juiciness and melting texture, high TSS/TA), whilst plums coated with GA 10% appear on the negative side of F1, associating with sensory and instrumental attributes that describe the profile of an unripe to semi-ripe plum (green aroma, unripe flavour, light peel appearance, opaque flesh appearance, sourness, firm texture, high flesh firmness, high peel colour parameters, high TA).

Interestingly, TSS was found to have a negative relationship with sweet taste (r = -0.300); therefore, TSS may not be a good measure of sweetness perceived by the consumer as previously reported (Lado *et al.*, 2014; Melgarejo *et al.*, 2014). The perception of sweetness in plums may be influenced by the presence of acids and aroma compounds contributing sweet notes to the overall flavour of the plum (Altisent *et al.*, 2008).

A strong, positive relationship was observed between flesh firmness assessed instrumentally, and green aroma (r = 0.768), unripe flavour (r = 0.807), firm texture (r = 0.839) and sour taste (r =

0.751) assessed in the sensory analysis (Table 6). Flesh firmness is widely used to assess fruit quality; therefore, it could also be used to predict these sensory attributes.

Regardless of treatment, no fermented aroma or fermented flavour was detected in the sensory analysis. Although coating application reduced respiration rate, oxygen levels must have been maintained such that anaerobic conditions were not created within the fruit, initiating the formation of fermentative volatiles.

3.7. Evaluation of coatings as a green replacement technology for HDPE bags

When plums were coated and packed without HDPE bags during cold storage, no significant difference ($p \geq 0.05$) was observed in flesh firmness (35.65-45.65 N) and peel colour parameters (L* 45.69-48.75 and *h*° 28.08-30.26) compared to control plums packed with HDPE bags (flesh firmness = 41.52 N, L* = 45.38 and *h*° = 27.87) at the end of cold storage (Table 7). Respiration rate in plums coated with GA 2% (33.08 mL CO^2/kg.h), GA 10% (33.74 mL CO^2/kg.h) and GA 5% + PSO (27.29 mL CO^2/kg.h) did not differ significantly ($p \geq 0.05$) from control plums packed with HDPE bags (30.47 mL CO^2/kg.h); therefore, coating application may have created a similar modified atmosphere in plums compared to that created by the HDPE bags within the carton (Mahfoudhi & Hamdi, 2015). As a result, fruit metabolic activity may have been similar between treatments, resulting in comparable physico-textural changes during cold storage.

The potential of coating application to eliminate the need for HDPE bags may be limited by coating moisture barrier properties. In coated plums packed without HDPE bags, weight loss (4.39% - 6.70%) and shrivel incidence (25.25% - 67.17%) were significantly ($p<0.05$) higher compared to control plums packed with HDPE bags (weight loss = 0.88% and shrivel incidence = 5.56%) at the end of cold storage.

To our knowledge, this is the first study to directly compare the effect of edible coating application to the use of HDPE bags to reduce postharvest losses in exported plums during the shipment period (-0.5°C and 90% RH cold storage for six weeks).

4. Conclusion and recommendations

The commercial viability of coating application proved promising throughout this study. Of all the coatings investigated, GA 10% performed best. The addition of the bioactive ingredients (pomegranate seed oil and ascorbic acid) did not have a significant effect on coating functionality. GA 10% significantly ($p<0.05$) reduced fruit softening, colour changes, acidity losses and increases in TSS, BrimA and TSS/TA throughout storage compared to control plums. Plums coated with GA 10% were also found to be microbially safe, with no faecal coliforms detected, and total coliforms

falling within specified limits. Furthermore, descriptive sensory analysis characterised plums coated with GA 10% as having unripe to semi-ripe sensory attributes at 5 d shelf life, compared to control plums which were characterised with a ripe to overripe profile. This suggests that GA 10% could extend the shelf life of 'African Delight™' plums beyond the current five day end point of commercial sale, with fruit maintaining quality for a minimum of 10 days at shelf life conditions. This observation was confirmed in the instrumental measurements, where fruit coated with GA 10% retained firmness (14.04 N), peel colour (L* = 34.67 and *h*° = 6.37) and TSS (15.60 °Brix) at 15 d under shelf life conditions. However, coatings were not successful in significantly reducing weight loss or shrivel development throughout storage. Therefore, future studies should focus on optimising both coating moisture barrier properties as well as processing conditions in packhouses whilst keeping in mind commercial viability and the infrastructure available. Shrivel may be reduced if fruit are coated immediately after harvest, minimising moisture loss before coating application. Additionally, coating integrity may be improved if fruit are allowed to dry post-coating, before being packed. These recommendations, however, can be challenging to implement in commercial environments where fruit volumes are exceptionally high and pack lines have limited capacities. Therefore, a potential solution could be layer-by-layer coating application whereby fruit could pass through the pack line more than once, consequently increasing coating coverage. Furthermore, the prospect of pre-harvest edible coatings may be a potential solution to reducing postharvest moisture loss in the holding period, before fruit are washed and then re-coated with a postharvest edible coating.

In addition to reducing postharvest quality losses, edible coatings were observed to be a potential green replacement technology for HDPE bags, however, high weight loss and shrivel incidence limited this potential. Therefore, future studies should optimise coating moisture barrier properties, with the aim of eliminating the need for HDPE bags during export. However, even if HDPE bags cannot be completely eliminated, coating application may be able to reduce the amount of plastic used to package export plums. For instance, instead of a voluminous bag, a single plastic sheet used to line the top of the carton may effectively maintain fruit quality when used in combination with edible coatings.

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Table 1. Peel lightness (L*) and hue angle (*h*°) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days)

Treatment	Peel lightness (L*)			Peel hue angle (*h*°)		
Cold storage (-0.5°C)	Week 2	Week 4	Week 6	Week 2	Week 4	Week 6
GA 2%	47.10±1.55*	44.51±1.33*	44.10±1.11*	31.50±1.16^{ab}	29.65±1.09^{ab}	28.99±1.06*
GA 5%	47.02±1.35	45.78±1.40	45.43±1.20	29.86±1.34^{ab}	26.15±1.04^{b}	28.02±1.05
GA 10%	47.91±1.28	46.71±1.13	46.20±1.15	32.52±1.68^{ab}	31.24±1.32^{a}	29.99±1.38
GA 5% + PSO	45.37±1.35	44.77±1.27	44.09±1.12	28.26±1.81^{b}	28.06±1.67^{ab}	26.59±1.42
GA 5% + AA	48.67±1.54	46.55±1.45	45.71±1.32	31.70±1.96^{ab}	29.45±1.59^{ab}	27.56±1.26
Sta-fresh	48.20±1.54	46.62±1.48	45.78±1.33	33.00±1.56^{ab}	31.44±1.43^{a}	29.68±1.26
Control	48.55±1.90	46.89±1.74	45.38±1.84	33.96±1.98^{a}	30.74±1.57^{a}	27.87±1.22
Prob. > F						
Treatment	0.0613			0.0002		
Time	<0.0001			<0.0001		
Treatment x time	1.0000			0.9761		
Shelf life (20°C)	Day 5	Day 10	Day 15	Day 5	Day 10	Day 15
GA 2%	34.14±0.62^{b}	32.85±0.62*	32.61±0.57^{b}	11.06±0.85^{b}	4.93±0.97^{ab}	3.11±0.79^{bc}
GA 5%	34.74±0.58^{ab}	33.54±0.59	33.81±0.64^{ab}	10.91±0.98^{b}	4.44±0.90^{b}	3.78±0.73^{abc}
GA 10%	36.96±0.85^{a}	34.16±0.70	34.67±0.68^{a}	14.89±1.24^{a}	7.97±1.27^{a}	6.37±1.05^{a}
GA 5% + PSO	35.81±0.72^{ab}	32.58±1.21	33.70±0.73^{ab}	11.85±1.11^{ab}	5.85±1.08^{ab}	4.05±0.89^{abc}
GA 5% + AA	35.34±0.89^{ab}	33.11±0.74	32.28±0.64^{b}	10.26±1.39^{b}	3.36±1.42^{b}	2.61±1.05^{c}
Sta-fresh	35.55±0.95^{ab}	33.17±0.82	32.46±0.71^{b}	14.53±0.98^{a}	7.82±0.97^{a}	5.52±1.07^{ab}
Control	34.36±0.69^{b}	32.11±0.48	32.23±0.59^{b}	9.48±1.02^{b}	3.09±0.98^{b}	2.15±0.93^{c}
Prob. > F						
Treatment	0.0386			<0.0001		
Time	<0.0001			<0.0001		
Treatment x time	0.9822			0.0002		

Means ± standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. Peel lightness at harvest was 48.36 ± 1.76; Peel hue angle at harvest was 33.46 ± 1.76; *not significant.

Table 2. Flesh lightness (L*) hue angle (*h*°) in 'African Delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days)

Treatment	Peel lightness (L*)			Peel hue angle (*h*°)		
Cold storage (-0.5°C)	Week 2	Week 4	Week 6	Week 2	Week 4	Week 6
GA 2%	81.60±0.92^{d}	82.35±1.10^{c}	72.06±1.05^{b}	84.10±0.88^{b}	84.97±0.57^{ab}	83.15±0.86^{ab}
GA 5%	86.46±2.22^{bcd}	87.66±1.77^{b}	87.55±1.39^{a}	83.73±1.14^{b}	85.26±0.68^{ab}	83.80±1.31^{ab}
GA 10%	87.59±1.66^{abc}	87.03±1.45^{bc}	88.38±2.25^{a}	84.97±1.41^{ab}	85.41±0.71^{ab}	84.35±1.54^{a}
GA 5% + PSO	91.38±2.32^{ab}	88.32±2.20^{b}	84.82±2.04^{a}	83.21±1.03^{b}	82.83±1.19^{b}	81.77±1.02^{ab}
GA 5% + AA	92.77±2.38^{a}	87.51±1.91^{b}	85.22±1.41^{a}	85.93±0.95^{ab}	83.76±1.04^{ab}	82.48±1.25^{ab}
Sta-fresh	87.77±1.43^{abc}	89.55±1.86^{b}	88.05±1.80^{a}	84.99±0.84^{ab}	84.11±1.00^{ab}	83.46±1.19^{ab}
Control	84.52±1.25^{cd}	97.10±1.35^{a}	88.14±1.58^{a}	87.25±0.69^{a}	86.45±0.79^{a}	80.44±1.25^{b}
Prob. > F						
Treatment	<0.0001			0.3819		
Time	0.0003			<0.0001		
Treatment x time	<0.0001			0.3326		
Shelf life (20°C)	Day 5	Day 10	Day 15	Day 5	Day 10	Day 15
GA 2%	75.80±1.25^{c}	84.51±1.69^{b}	79.66±1.63^{bc}	76.96±1.21^{bc}	70.96±1.60^{bc}	65.43±1.62^{bc}
GA 5%	76.68±1.18^{c}	80.06±1.73^{bc}	74.44±2.42^{c}	74.98±1.24^{c}	66.48±2.17^{cd}	59.24±3.07^{cd}
GA 10%	86.64±2.72^{a}	91.16±1.49^{a}	80.74±1.93^{ab}	81.48±1.00^{a}	79.30±1.16^{a}	67.47±2.85^{b}
GA 5% + PSO	85.34±2.03^{ab}	83.40±2.73^{bc}	82.78±1.42^{ab}	78.93±1.53^{abc}	64.74±3.61^{d}	65.72±1.82^{bc}
GA 5% + AA	86.99±1.93^{a}	84.86±1.28^{b}	86.09±1.66^{a}	79.79±1.13^{ab}	73.68±1.18^{b}	76.75±1.18^{a}
Sta-fresh	80.97±1.78^{bc}	78.29±1.60^{c}	73.95±2.99^{c}	77.52±1.45^{abc}	68.87±2.40^{bcd}	61.69±3.16^{bcd}
Control	86.03±1.57^{ab}	72.67±1.84^{d}	64.04±2.15^{d}	78.27±1.43^{abc}	67.36±1.69^{cd}	54.89±2.83^{d}
Prob. > F						
Treatment	<0.0001			<0.0001		
Time	<0.0001			<0.0001		
Treatment x time	<0.0001			<0.0001		

Means ± standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, flesh lightness was 85.46 ± 1.82 and flesh hue angle was 85.67 ± 1.17; *not significant.

Table 3. Titratable acidity (TA, % malic acid) and total soluble solids (TSS, °Brix) in 'African Delight™' plums throughout a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days)

	Total soluble solids (TSS, °Brix)			Titratable acidity (TA, % malic acid)		
Treatment	Week 2	Week 2	Week 4	Week 6	Week 4	Week 6
Cold storage (-0.5°C)						
GA 2%	17.58±0.46*	0.84±0.03*	0.73±0.05^{c}	0.76±0.04^{ab}	16.86±0.46^{b}	17.20±0.57*
GA 5%	17.56±0.52	0.96±0.04	0.87±0.03^{ab}	0.84±0.03^{b}	17.38±0.22^{ab}	17.42±0.38
GA 10%	18.40±0.56	1.01±0.03	0.91±0.02^{b}	0.83±0.02^{b}	18.68±0.22^{a}	17.00±0.51
GA 5% + PSO	17.44±0.34	0.95±0.03	0.80±0.03^{ac}	0.75±0.02^{ab}	18.02±0.54^{ab}	17.18±0.42
GA 5% + AA	17.90±0.39	1.00±0.04	0.80±0.03^{ac}	0.77±0.02^{ab}	17.40±0.32^{ab}	17.28±0.45
Sta-fresh	17.06±0.36	0.96±0.03	0.87±0.03^{ab}	0.76±0.03^{ab}	18.14±0.25^{ab}	16.80±0.46
Control	17.14±0.58	0.96±0.01	0.84±0.01^{ab}	0.67±0.05^{a}	16.88±0.77^{b}	16.64±0.54
Prob. > F						
Treatment	0.2722			0.0043		
Time	0.0904			<0.0001		
Treatment x time	0.7619			0.2779		
Shelf life (20°C)	Day 5	Day 5	Day 10	Day 15	Day 10	Day 15
GA 2%	17.02±0.37*	0.47±0.02^{b}	0.45±0.04^{b}	0.44±0.01^{ab}	16.88±0.49^{ab}	17.02±0.35^{ab}
GA 5%	17.38±0.48	0.54±0.02^{ab}	0.45±0.02^{b}	0.39±0.03^{b}	16.66±1.11^{ab}	15.26±0.54^{c}
GA 10%	17.20±0.97	0.57±0.04^{a}	0.48±0.02^{b}	0.40±0.02^{b}	17.88±0.53^{a}	15.60±0.27^{bc}
GA 5% + PSO	17.16±0.54	0.55±0.02^{a}	0.40±.0.4^{b}	0.40±0.01^{b}	16.92±0.57^{ab}	15.84±0.42^{bc}
GA 5% + AA	17.88±0.49	0.56±0.01^{a}	0.46±0.02^{b}	0.45±0.02^{ab}	14.60±1.50^{b}	17.24±0.70^{ab}
Sta-fresh	17.58±0.46	0.57±0.03^{a}	0.51±0.03^{b}	0.47±0.02^{a}	18.94±0.89^{a}	17.00±0.71^{ab}
Control	16.30±0.36	0.51±0.02^{ab}	0.62±0.05^{a}	0.45±0.01^{ab}	18.84±0.25^{a}	17.96±0.56^{a}
Prob. > F						
Treatment	0.2633			0.0770		
Time	0.1417			<0.0001		
Treatment x time	0.0009			<0.0001		

Means ± standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, total soluble solids were 17.28 ± 0.46 °Brix and titratable acidity was 0.95 ± 0.05% malic acid; *not significant.

Table 4. TSS/TA and BrimA in 'African Delight™' plums throughout a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days)

Treatment	TSS/TA			BrimA		
Cold storage (-0.5°C)	Week 2	Week 4	Week 6	Week 2	Week 4	Week 6
GA 2%	21.49±0.39^{a}	23.35±0.93^{a}	22.84±0.72^{ab}	13.38±0.39*	13.21±0.22*	13.41±0.37*
GA 5%	17.71±0.69^{b}	20.02±0.43^{c}	20.71±0.44^{b}	12.74±0.35	13.03±0.17	13.20±0.22
GA 10%	18.57±0.70^{b}	20.55±0.36^{bc}	20.50±0.62^{b}	13.37±0.46	14.13±0.21	12.85±0.49
GA 5% + PSO	18.41±0.80^{b}	22.62±0.84^{ab}	23.08±0.84^{ab}	12.71±0.44	14.02±0.48	13.45±0.45
GA 5% + AA	17.67±0.33^{b}	21.82±0.93^{abc}	22.60±0.66^{ab}	12.88±0.23	13.39±0.36	13.45±0.41
Sta-fresh	18.35±0.52^{b}	20.85±0.72^{bc}	22.37±1.09^{ab}	12.25±0.24	13.77±0.27	13.02±0.50
Control	17.96±0.75^{b}	20.31±1.07^{bc}	25.48±1.93^{a}	12.35±0.58	13.54±1.05	13.31±0.56
Prob. > F						
Treatment	0.0040			0.8825		
Time	<0.0001			0.0002		
Treatment x time	0.0400			0.9268		
Shelf life (20°C)	Day 5	Day 10	Day 15	Day 5	Day 10	Day 15
GA 2%	36.35±1.30^{a}	36.59±3.20^{ab}	38.38±1.18*	14.67±0.37*	14.63±0.47^{ab}	14.80±0.37^{ab}
GA 5%	32.62±1.37^{a}	38.27±2.84^{ab}	40.14±3.63	14.70±0.43	14.42±1.18^{ab}	13.31±0.57^{b}
GA 10%	23.19±5.87^{b}	36.33±1.39^{ab}	39.60±1.16	14.23±0.85	15.46±0.53^{a}	13.62±0.19^{b}
GA 5% + PSO	31.40±0.89^{a}	41.18±5.05^{a}	40.02±1.12	14.42±0.47	14.92±0.52^{ab}	13.86±0.42^{ab}
GA 5% + AA	31.83±0.65^{a}	31.45±2.56^{b}	38.93±3.13	15.07±0.45	12.32±1.43^{b}	14.99±0.75^{ab}
Sta-fresh	30.89±1.14^{a}	38.56±1.70^{ab}	35.65±2.14	14.72±0.40	16.40±0.78^{a}	15.12±1.00^{ab}
Control	32.16±0.59^{a}	29.03±2.59^{b}	39.96±0.82	13.76±0.27	15.73±0.27^{a}	15.71±0.50^{a}
Prob. > F						
Treatment	0.1612			0.2517		
Time	<0,0001			<0,0001		
Treatment x time	0.0137			0.0128		

Means ± standard errors with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test. P-values in red are significant. At harvest, TSS/TA was 18.45 ± 0.92 and BrimA was 12.55 ± 0.48; *not significant.

Table 5. Microbial counts (mean log CFU/g) of 'African Delight™' plums at 5 d shelf life

	Aerobic mesophilic bacteria	Total coliforms	Faecal coliforms
GA 10%	3.10±0.01[b]	3.02±0.02[a]	ND
Sta-fresh	3.50±0.09[ab]	3.03±0.04[a]	ND
Control	4.31±0.37[a]	< 1[b]	ND

Treatment means with different letters within the same microbial test are significantly different ($p<0.05$) according to Duncan's multiple range test.

Table 6. Pearson correlation coefficients (*r*) among instrumental and sensory attributes of 'African Delight™' plum treatments (GA 10%, Sta-fresh and control) at 5 d shelf life

Instrumental attributes	Sensory attributes											
	Aroma		Appearance		Flavour			Taste		Texture		
	Plum	Green	Peel	Flesh	Plum	Unripe	Overripe	Sour	Sweet	Firmness	Melting	Juiciness
TSS	-0,229	0,305	-0,262	-0,211	-0,260	0,286	0,037	0,254	-0,300	0,233	-0,255	-0,281
TA	-0,359	0,249	-0,190	-0,372	-0,309	0,221	-0,377	0,257	-0,220	0,278	-0,326	-0,289
TSS/TA	0,229	-0,106	0,083	0,254	0,194	-0,100	0,361	-0,141	0,099	-0,166	0,202	0,153
BrimA	-0,107	0,211	-0,189	-0,086	-0,151	0,202	0,148	0,160	-0,214	0,134	-0,142	-0,177
Flesh firmness	**-0,739**	**0,768**	**-0,745**	**-0,800**	**-0,812**	**0,807**	**-0,650**	**0,751**	**-0,790**	**0,839**	**-0,826**	**-0,801**
Peel L*	**-0,647**	**0,706**	**-0,713**	**-0,657**	**-0,633**	**0,686**	-0,468	**0,534**	**-0,581**	**0,604**	**-0,616**	**-0,620**
Peel *h*°	**-0,718**	**0,743**	**-0,734**	**-0,809**	**-0,790**	**0,789**	**-0,583**	**0,711**	**-0,737**	**0,791**	**-0,825**	**-0,777**
Flesh L*	0,058	0,031	-0,056	0,028	-0,039	-0,013	0,046	-0,034	0,048	-0,040	-0,031	-0,032
Flesh *h*°	-0,186	0,381	-0,402	-0,340	-0,333	0,411	0,081	0,277	-0,336	0,301	-0,351	-0,374

Values highlighted in **bold** represent moderate to strong (>0.5) correlations.

Table 7. Various instrumental quality parameters measured at the end of the cold storage period (-0.5°C and 90% RH for 6 weeks) in control 'African Delight™' plums packed with HDPE bags, and coated 'African Delight™' plums packed without HDPE bags

Treatment	Respiration rate (mL CO2/kg.h)	Weight loss (%)	Shrivel incidence (cumulative %)	Flesh firmness (N)	Lightness (L*) of plum peel	Hue angle (*h*°) of plum peel
Control	30.47±1.60^{bc}	0.88±0.13^{d}	5.56±2.20^{e}	41.52±2.01^{abc}	45.38±1.84*	27.87±1.22*
GA 2%	33.08±0.97^{b}	4.62±0.35^{bc}	67.17±4.82^{a}	35.65±1.49^{c}	46.13±1.17	29.82±1.09
GA 5%	38.46±0.00^{a}	4.39±0.28^{c}	48.99±3.07^{bc}	39.52±2.69^{abc}	45.69±0.89	28.08±0.79
GA 10%	33.74±0.99^{b}	5.68±0.33^{ab}	58.59±3.54^{ab}	38.42±1.61^{bc}	46.72±1.91	30.26±1.79
GA 5% + PSO	27.29±1.75^{c}	5.72±0.39^{ab}	39.39±6.12^{cd}	42.25±2.60^{ab}	48.75±1.55	29.81±1.57
GA 5% + AA	42.44±1.75^{a}	6.70±0.67^{a}	25.25±8.08^{d}	45.65±1.40^{a}	46.68±1.50	29.34±1.43

Means±standard error with different letters within columns are significantly different ($p<0.05$) according to Duncan's multiple range test; *not significant.

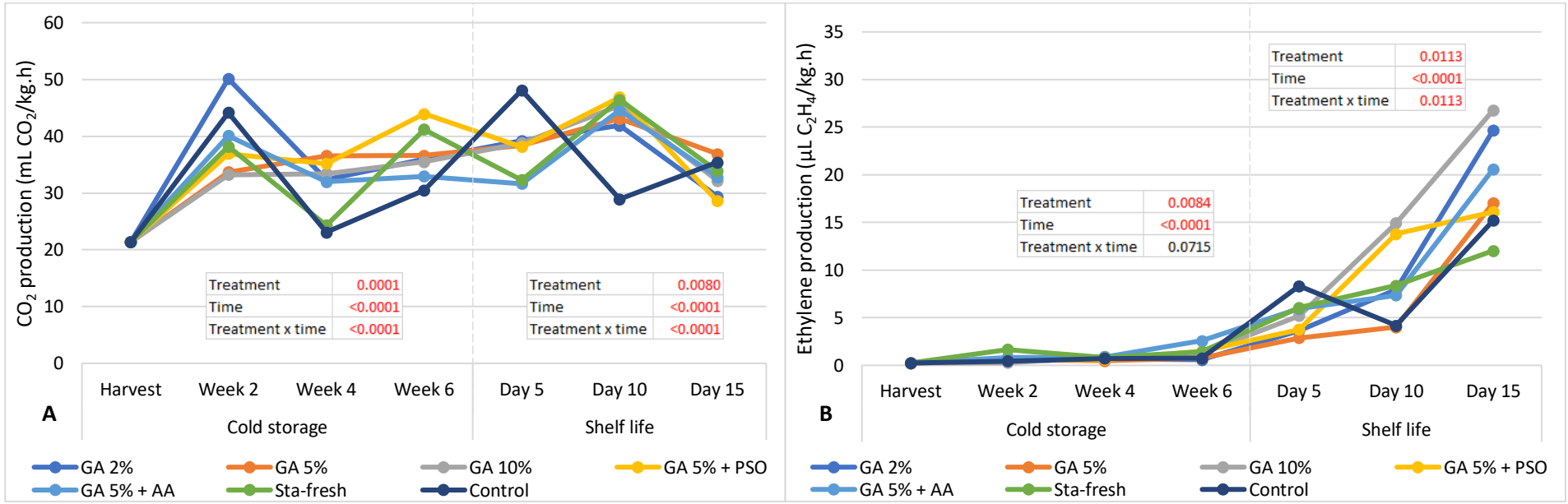

Figure 1. Physiological responses (A - respiration rate and B - ethylene production) in 'African delight™' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days). P-values in red are significant.

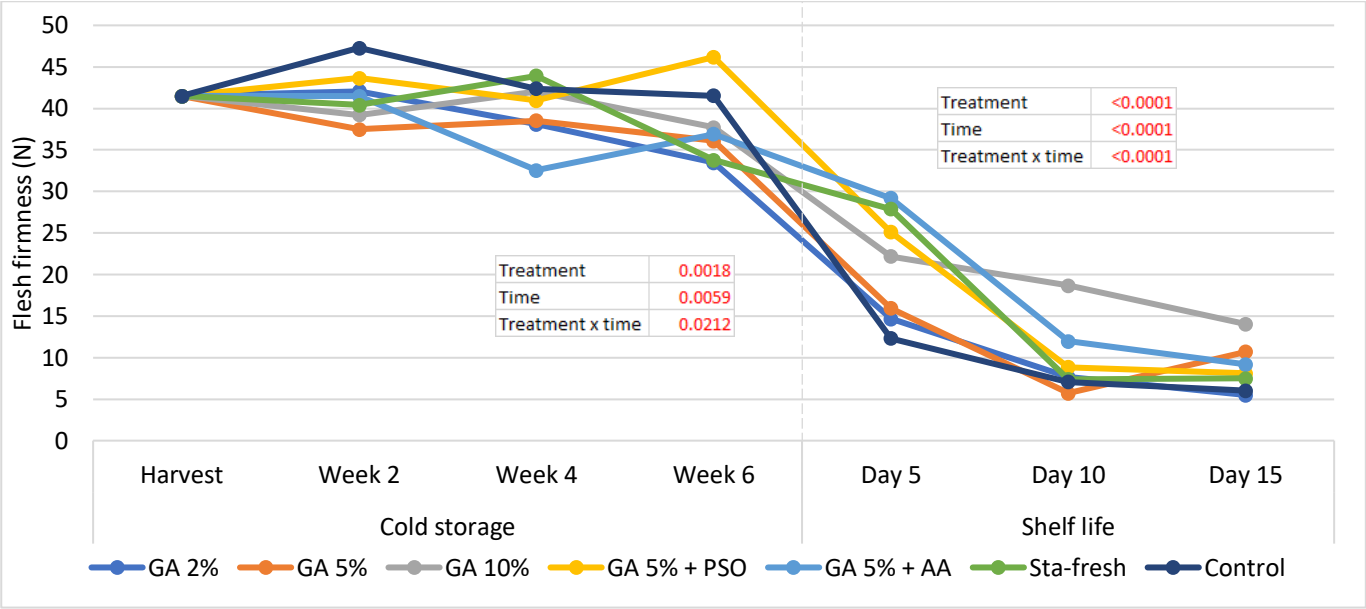

Figure 2. Flesh firmness (N) in 'African delight' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days). P-values in red are significant.

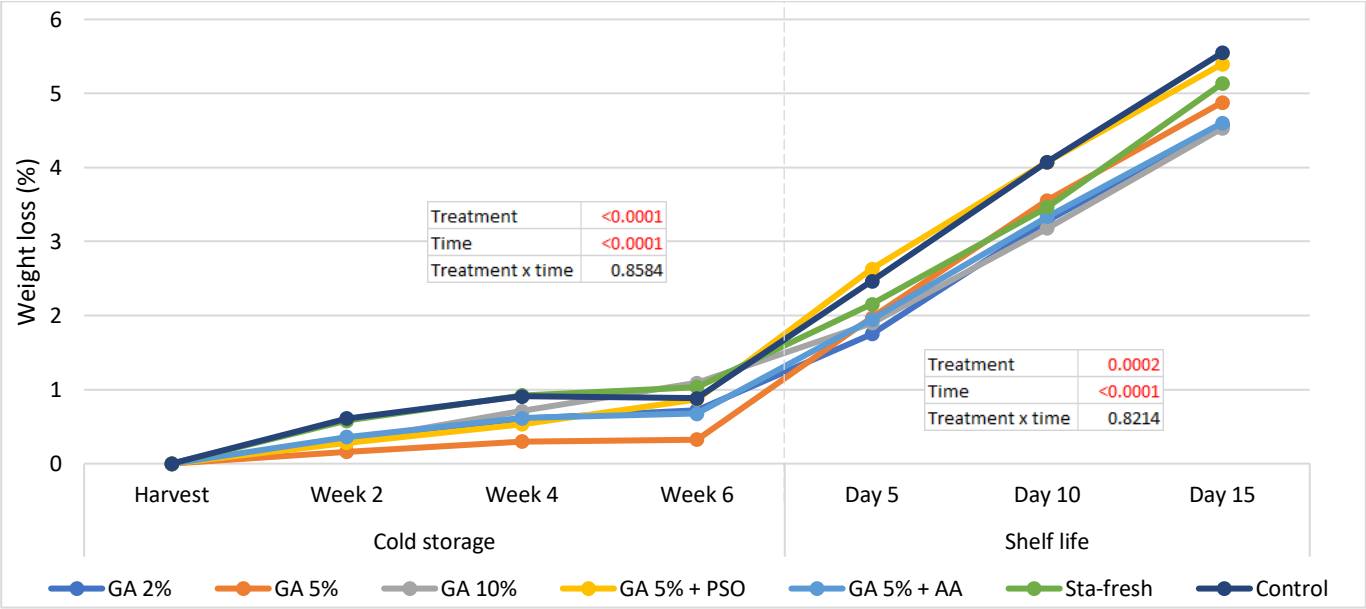

Figure 3. Weight loss (%) in 'African delight' plums during a simulated shipping period (cold storage; -0.5°C and 90% RH for 6 weeks) and a subsequent shelf life period (20°C and 80% RH for 15 days). P-values in red are significant.

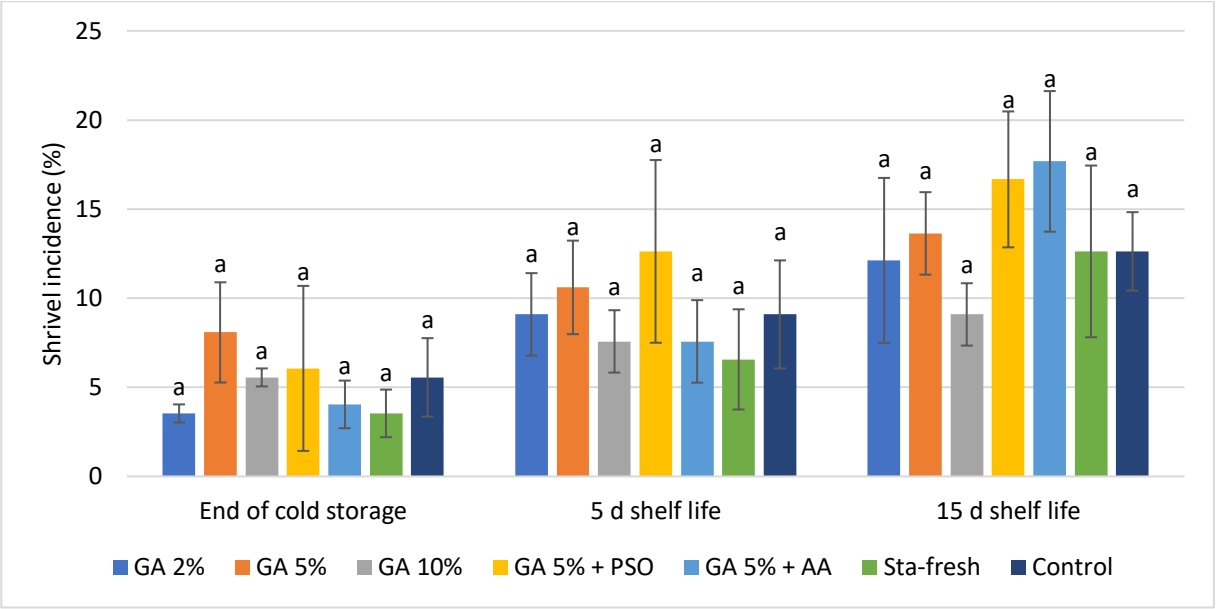

Figure 4. Cumulative shrivel occurrence in 'African Delight™' plums at the end of the cold storage period (-0.5°C and 90% RH for 6 weeks) and after 5 and 15 d shelf life period (20°C and 80% RH). Means with different letters within storage intervals are significantly different ($p<0.05$) according to Duncan's multiple range test.

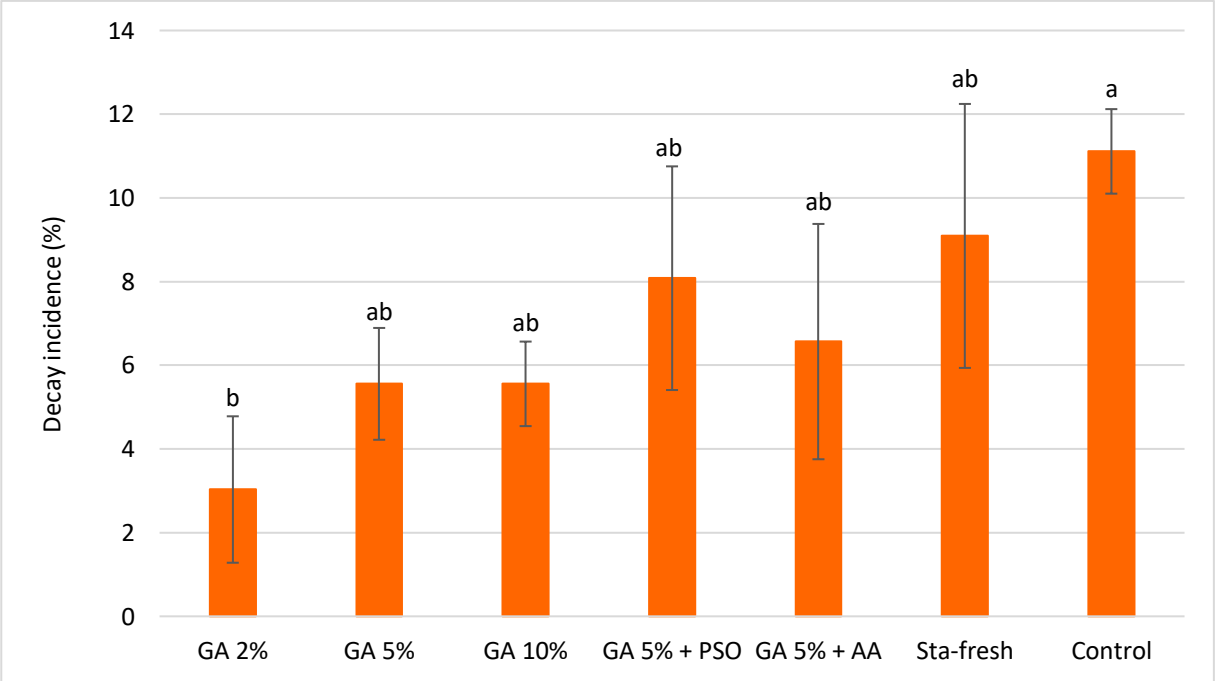

Figure 5. Cumulative decay incidence in 'African Delight™' plums at the end of storage (-0.5°C and 90% RH for 6 weeks, followed by 20°C and 80% RH for 15 days). Means with different letters are significantly different ($p<0.05$) according to Duncan's multiple range test.

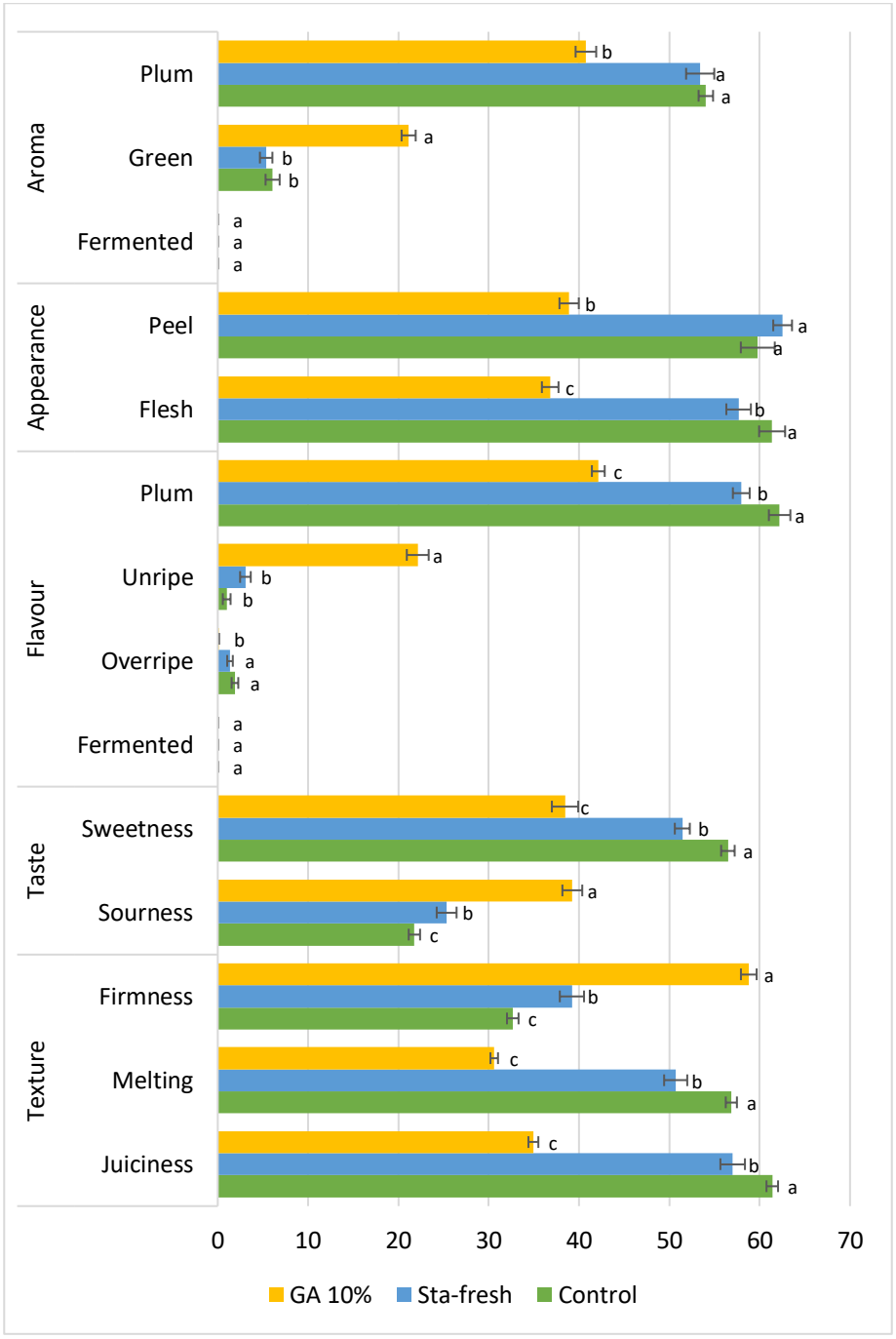

Figure 6. Mean scores per attribute measured by the trained sensory panel for 'African Delight™' plums (GA 10%, Sta-fresh and control) at 5 d shelf life. Means with different letters within attributes are significantly different ($p<0.05$) according to Duncan's multiple range test.

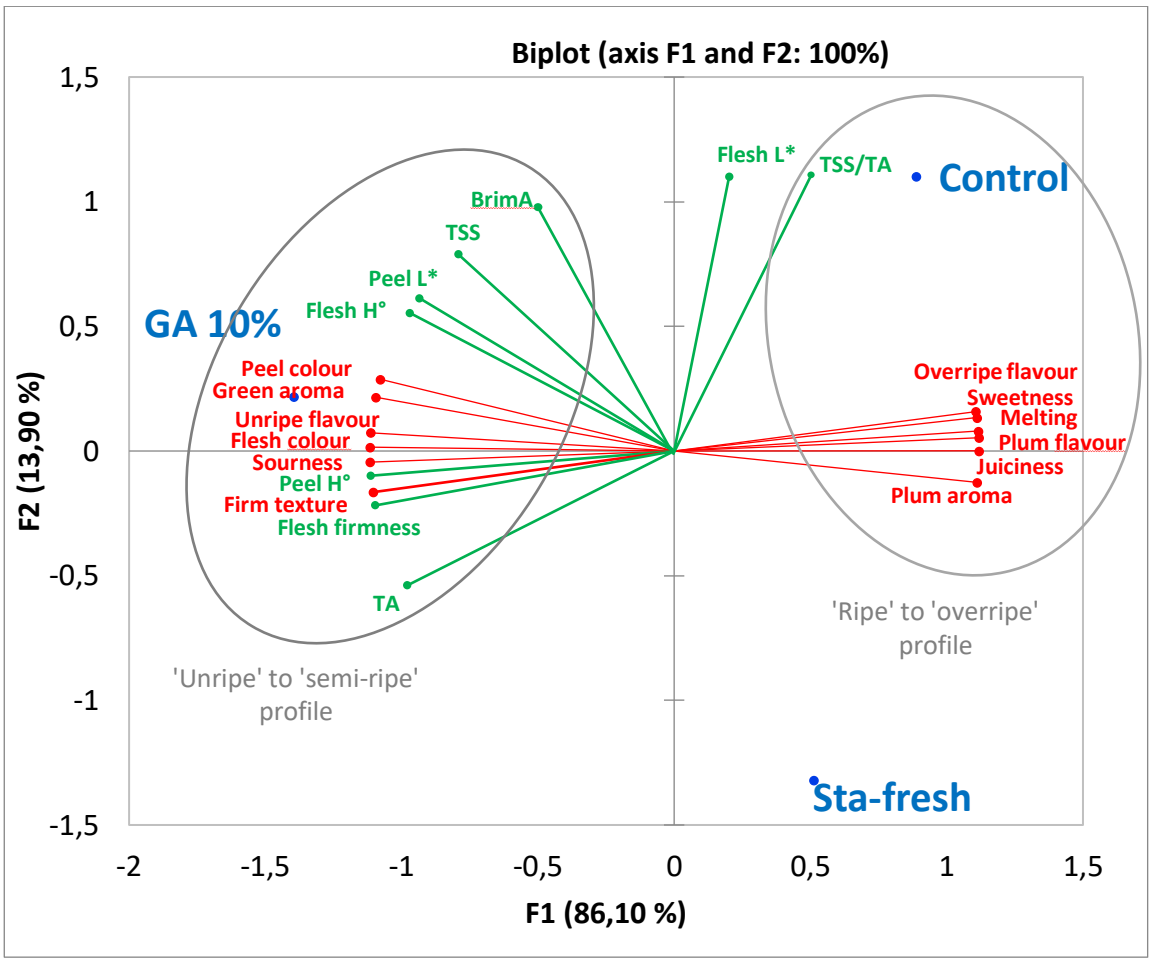

Figure 7. Principal component analysis of the first two factors (F1 and F2) based on sensory analysis (red) and instrumental analysis (green) of 'African Delight™' plums (GA 10%, Sta-fresh and control) at 5 d shelf life.

CHAPTER 5: GENERAL DISCUSSION AND CONCLUSION

Plums are highly perishable in nature, making them susceptible to high postharvest losses such as overripeness, shrivel and decay. Most plums are climacteric; therefore, they produce ethylene during ripening (Farcuh *et al*., 2018). The production of ethylene triggers several biochemical and enzymatic reactions within the fruit, consequently increasing respiration rate. The ripening process causes several physico-chemical changes that improve the eating quality of fruit; however, these changes also limit the economic value of plums as a result of short shelf life.

The South African stone fruit industry is export-oriented and like other stone fruits, plums are subjected to a very long handling chain, with shipping periods lasting up to six weeks. Thus, the industry relies heavily on postharvest technologies to suppress the ripening process and minimise moisture losses during the long sea freight. Although South Africa is one of the largest exporters of plums in the world, the level of competitiveness between international markets forces the South African plum industry to constantly strive towards achieving a higher export plum quality. Despite the adoption of low storage temperatures and high density polyethylene (HDPE) bags to reduce postharvest losses during export, the incidence of fruit rejection on account of quality-related issues is still unfavourably high (Kritzinger *et al.* 2018; P. Roussouw 2019, personal communication, 26 July). Fruit often have to be repacked upon arrival at the export market, which has a detrimental effect on the income generated for the South African plum industry.

Edible coatings have been identified as a promising technology for the control of postharvest losses. Several studies have reported edible coatings to maintain plum quality during storage by reducing the ripening rate of the fruit, resulting in a shelf life extension (Valero *et al.*, 2013; Kumar *et al.*, 2017; Thakur *et al*., 2018). Postharvest losses are controlled through the formation of a semi-permeable barrier around the surface of the fruit that limits moisture loss and gaseous exchange (Ncama *et al*., 2018). Coating functionality is similar to that of the plum's natural waxy cuticle. The cuticle covers the fruit's surface, providing a physical barrier to transpiration and respiration, and protecting the fruit against biological attack (Lara *et al*., 2014). However, the integrity of this cuticle is easily compromised during postharvest handling practices and washing procedures, leaving fruit susceptible to high rates of respiration and transpiration (Maqbool *et al.*, 2011; Thakur *et al.*, 2018). Hence, the application of an additional protective barrier may help control postharvest losses.

In paper 1, scanning electron microscopy was used to gain a better understanding of coating functionality. Special attention was given to lenticels on the fruit's surface, as these organelles act as points of accelerated respiration and major channels for postharvest moisture loss (Díaz-Pérez *et al*.,

2007). Coatings were observed to completely cover the plum's lenticels, in contrast to the plum's natural waxy cuticle, where visible breaks over the lenticel were observed. Therefore, coatings may provide a protective layer with improved barrier properties compared to those offered by the fruit's natural waxy cuticle. In addition, the lenticel of an uncoated plum sample that had been subjected to a preliminary washing step was bare, with no cuticular wax left intact. Thus, coating application could protect fruit from high respiration and transpiration rates that often result from practices that take place in the orchard and packhouse that remove the cuticle.

The aim of paper 1 was to identify an edible coating that could control postharvest losses and potentially extend the shelf life of 'African Delight™' plums. In a laboratory-scale trial, six different edible coatings were screened during a simulated shipping period (cold storage, -0.5 ± 2°C and 90 ± 5% RH for five weeks) and a subsequent shelf life period (20 ± 2°C and 80 ± 5% RH for 20 days). A volatile analysis confirmed that coating application did not result in the formation of off-flavours as a result of anaerobic respiration. Plums coated with alginate, chitosan and gum arabic performed best, maintaining their colour, texture and acidity throughout storage. At 20 d shelf life, coated fruit resembled that of control fruit at 5 to 10 d shelf life. Thus, coating application may extend plum shelf life. The delay in physico-chemical changes could indicate a reduced rate of ripening as a result of the suppressed respiration rate and ethylene production observed in coated fruit (Maftoonazad *et al.*, 2008; Valero *et al.*, 2013; Kumar *et al.*, 2017). However, alginate and chitosan did not significantly control weight loss and shrivel incidence in plums throughout storage. Although unclear, coating integrity may have been reduced during storage as a result of lipid migration or poor plasticity (Reinoso *et al.*, 2008).

Gum arabic, however, significantly ($p<0.05$) reduced weight loss and shrivel incidence throughout storage, in addition to delaying physico-chemical changes and reducing decay. Gum arabic is a polysaccharide-based hydrocolloid that has been reported to have good emulsifying properties (Mahfoudhi *et al.*, 2014). These properties may have resulted in a stable, even dispersion of lipid particles with a small mean droplet size throughout the coating. Therefore, the moisture barrier properties of gum arabic may have been superior to the other coatings as a result of improved coating functionality throughout storage. A strong positive relationship ($R^2 = 0.653$; $r = 0.808$) was observed between weight loss and shrivel incidence in 'African Delight™' plums. Therefore, the ability of gum arabic to control shrivel development may be linked to the moisture barrier properties of the coating. Shrivel is a major postharvest challenge in the export of many plum cultivars; thus, the potential of edible coatings to control shrivel during export holds huge economic value.

After identifying gum arabic as the best edible coating to reduce postharvest losses and extend the shelf life of plums, it was important to validate the commercial viability of coating application,

as well as optimise coating formulation. In paper 2, several gum arabic (GA) based coatings, including GA 2%, GA 5%, GA 10%, GA 5% + pomegranate seed oil and GA 5% + ascorbic acid, were applied to plums in a working packhouse. The trial was conducted on a commercial-scale, where real-life postharvest handling practices were considered. After harvest, the plums were held at 10°C for one week, simulating the waiting period that may ensue before fruit are processed. Fruit were then washed and coated on a commercial pack line using an atomizer, and thereafter packed and stored at -0.5 ± 2°C and 90 ± 5% RH for six weeks, simulating the shipping period of exported plums, followed by 20 ± 2°C and 80 ± 5% RH for 15 days, as a subsequent shelf life period.

In the laboratory-scale trial, gum arabic was applied at 2% w/v. In the follow-up trials for commercial viability of coating application, the concentration of gum arabic was increased up to 10% w/v. Postharvest solutions are applied with a spraying action on commercial pack lines, contrasting to the dipping-action used in the laboratory-scale trial. Lerdthanangkul and Krochta (1996) and Zhong *et al*. (2014) have reported spraying to deposit less coating onto the fruit's surface compared to dipping, resulting in a thinner coating barrier being formed, or incomplete surface coverage. Therefore, gum arabic concentration was increased to maximise functionality in the commercial-scale trials. In addition, bioactive ingredients (pomegranate seed oil and ascorbic acid) were added to coatings in an attempt to improve coating functionality.

Of all the gum arabic-based coatings that were investigated, GA 10% performed best, delaying physico-chemical changes during storage by suppressing respiration and ethylene production. The addition of the bioactive ingredients did not have a significant effect on coating functionality. Descriptive sensory analysis conducted at 5 d shelf life characterised plums coated with GA 10% as having unripe to semi-ripe sensory attributes, compared to control plums which were characterised with a ripe to overripe profile. This suggests that GA 10% could extend the shelf life of 'African Delight™' plums beyond the current five day end point of commercial sale. However, coatings were not successful in significantly reducing weight loss or shrivel development throughout storage. The conditions of the commercial scale-trial may have reduced the functionality and moisture barrier properties of gum arabic, compared to those observed in the laboratory-scale trial. Major moisture loss could have occurred in the holding period (1 week at 10°C) before fruit were coated, minimising the effect of coatings on shrivel control. Additionally, coating coverage and thus barrier properties may have been reduced as a result of the spray-application on pack lines. As mentioned, spraying has been reported to deposit less coating onto the fruit surface compared to dipping, resulting in a thinner coating barrier being formed, or incomplete surface coverage. Furthermore, coating integrity may have been reduced by packing fruit before they were completely dry.

Despite the challenge of moisture loss and shrivel incidence, gum arabic exhibited promising potential as a commercial postharvest edible coating for plums. Coating application proved viable for commercial packhouses, as pack lines were equipped with atomizers for the application of postharvest solutions such as fungicides. In addition to exhibiting delayed ripening and physico-chemical changes, plums coated with GA 10% were also found to be microbially safe for human consumption when tested at 5 d shelf life.

Future studies should focus on optimising both coating moisture barrier properties as well as processing conditions in packhouses whilst keeping in mind commercial viability and the infrastructure available. Shrivel may be reduced if fruit are coated immediately after harvest. Additionally, coating integrity may be improved if a short drying period is implemented post-coating, before fruit are packed. These recommendations, however, can be challenging to implement in commercial environments where fruit volumes are exceptionally high and pack lines have limited capacities. Therefore, a potential solution could be layer-by-layer coating application whereby fruit could pass through the pack line more than once, consequently increasing coating coverage and thus functionality (Arnon-Rips & Poverenov, 2018). Furthermore, the prospect of pre-harvest edible coatings may be a potential solution to reducing postharvest moisture loss in the holding period, before fruit are washed and then re-coated with a postharvest edible coating.

In addition to reducing postharvest quality losses, the commercial application of edible coatings holds potential as a green replacement technology for the costly, unsustainable HDPE bags used to pack exported plums. In the commercial-scale trial, plums were coated with gum arabic and packed without HDPE bags during cold storage. At the end of the cold storage period (-0.5°C and 90% RH for six weeks), the physico-textural properties of coated fruit packed without HDPE bags resembled that of control plums packed with HDPE bags. Additionally, the respiration rate of coated plums packed without HDPE bags did not differ significantly from that of control plums packed with HDPE bags. Therefore, coating application may have created a similar modified atmosphere in plums compared to that created by the HDPE bags within the carton, resulting in comparable changes in postharvest quality during cold storage (Yaman & Bayoindirli, 2002). However, weight loss and shrivel incidence were significantly higher in coated plums packed without HDPE bags compared to control plums packed with HDPE bags. Therefore, the potential of coating application to eliminate the need for HDPE bags is limited by coating moisture barrier properties. Future studies should focus on optimising coating moisture barrier properties, with the aim of eliminating the need for HDPE bags during export.

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APPENDIX

Table 1. Volatile compounds in 'African Delight™' juice and their mean peak area percentages harvest, end of cold storage, 5 d shelf life and 20 d shelf life

	RT	Harvest	End of cold storage							5 d shelf life						20 d shelf life						
Compound			A	B	C	D	E	F	G	A	B	C	D	E	F	G	A	B	C	D	E	F	G
Alcohol																						
2-propen-1-ol	6.24																		0.14				
Ethanol	7.08	0.70	10.05	24.80	12.19	24.63	8.59	9.82	5.98	51.02	54.32	29.04	54.77	27.13	49.88	19.25	72.23	81.18	72.82	83.57	79.93	82.92	79.60
2-butanol	8.22																					0.02	
Propanol	10.95													0.06				0.18		0.36	0.45	0.20	0.19
2-methyl-1-propanol	13.76			0.25						0.24		0.13		0.13	0.14								
1-butanol	16.48													0.09		0.11	0.03	0.16	0.11	0.09	0.56	0.08	0.21
1-pentanol	19.41				0.76											0.88							
2-methyl-butan-1-ol	19.43		0.46	0.70	0.40	0.39	1.19	0.25	0.41	0.57	0.33	0.75	0.39	0.57		0.27	0.43	0.57	0.54	0.19	0.44	0.53	0.86
3-methyl-butan-1-ol	19.53		0.82	2.03		0.84		0.22	0.18	0.96	0.54	1.01	0.15	1.65	1.43		0.12				0.64		
1-octen-3-ol	21.15								0.08														
2-methyl-2-buten-1-ol	25.21																0.09	0.08	0.10		0.19		0.07
1-hexanol	26.66	53.22	31.01	38.01	50.11	39.66	56.99	46.04	57.21	10.32	15.78	20.06	15.04	23.21	16.73	16.37	0.81	3.92	5.81	1.50	5.52	1.28	3.85
1-octanol	27.05						1.80							0.40									
(Z)-3-hexenol	27.94	14.79	15.17	11.79	19.81	18.69	16.86	18.83	19.72	4.97	6.95	9.82	6.68	12.43	7.85	14.07	1.16	1.84	4.79	0.76	2.24	0.54	1.80
(E)-2-hexen-1-ol	28.86	0.55			0.16	0.12					0.12						0.40						
β-fenchyl alcohol	40.86																				0.35	0.14	0.18
Benzyl alcohol	44.20						0.23	0.10	0.28		0.71		0.03	0.49	0.06						0.25		0.04
Total alcohols		69.27	57.51	77.58	83.42	84.33	85.65	75.26	83.87	68.07	78.77	60.81	77.06	66.15	76.08	50.94	75.27	87.93	84.32	86.48	90.57	85.71	86.79
Aldehyde																							
Butanal, 3-methyl-	6.22	0.23		0.20							0.09						0.14	0.12	0.10	0.41		0.14	
Butanal, 2-methyl-	6.24	0.22	0.60		0.27			0.49	0.41		0.22		0.21				0.19	0.42	0.76	0.60		0.21	
Pentanal	6.27												0.19	0.20								0.11	
Hexanal	12.72	13.03	5.14	4.40	1.71	1.56	0.58	10.28	2.56	0.17	3.87	0.32	2.03	1.80	0.56	7.39	0.89	0.61	2.74	1.47		1.58	0.09
Heptanal	17.29								0.29			0.07								0.05			0.07
(E)-2-hexenal	19.40	0.78	0.41					0.34			0.15					0.33							
Benzaldehyde	34.06	1.35	0.10					1.60			0.79						0.21	0.26	0.10	0.11		0.35	
Total aldehydes		15.62	6.25	4.59	1.98	1.56	0.58	12.71	3.26	0.17	5.13	0.39	2.43	2.00	0.56	7.72	1.42	1.41	3.69	2.63	0.00	2.38	0.16
Ester																							
Ethyl acetate	5.63		15.52	6.92	5.35	5.34	1.51	1.17	0.76	23.81	4.61	22.45	7.85	8.10	14.07	6.02	17.00	6.86	5.16	7.53	5.60	6.36	7.81
Propyl acetate	8.27									0.22	0.12	0.05						0.12					
Ethyl butanoate	10.68									0.09	0.08		0.39		0.22		0.08	0.44	0.63	0.60	0.74	0.71	0.54
Ethyl 2-methylbutanoate	11.37																0.16	0.09		0.17	0.10	0.10	0.08

Table 1 (Continued). Volatile compounds in 'African Delight™' juice and their mean peak area percentages harvest, end of cold storage, 5 d shelf life and 20 d shelf life

Butyl acetate	12.21	1.01								0.07	0.31	0.36	0.29	0.52	0.24	0.31	0.11	0.38	0.19	0.11	0.28	0.18	0.52
Isoamyl acetate	14.35		0.77	0.28	0.25	0.14				0.16	0.04	0.64		0.17	0.13	0.11	0.02	0.03				0.07	
Ethyl crotonate	16.34																0.24	0.24	0.31	0.32	0.31	0.21	0.21
Ethyl hexanoate	19.86										0.21		0.12				0.17	0.12	0.14	0.13	0.06	0.16	0.03
Ethyl tiglate	20.20																0.23	0.03		0.11			
Hexyl acetate	22.24	3.15	9.19	4.02	3.33	2.70	5.85	3.62	5.28	2.68	4.48	6.09	4.61	10.09	3.02	10.29	0.57	0.95	1.23	0.70	0.45	0.96	2.14
(Z)-3-hexenyl acetate	24.61	9.22	9.22	2.33	2.51	2.49	3.16	3.34	3.91	3.27	4.79	6.37	5.39	8.73	3.25	7.44	0.03	0.86	0.53	0.17		0.16	0.46
(Z)-2-hexenyl acetate	25.44		0.03														0.18						
Hexyl formate	26.65							0.60	0.99							10.98	0.77						
Heptyl isobutyrate	44.28																0.22						
Total esters		13.39	34.74	13.55	11.45	10.66	10.52	8.73	10.94	30.30	14.64	35.97	18.64	27.62	20.92	35.16	19.79	10.14	8.20	9.84	7.53	8.90	11.80
Ketone																							
2-heptanone	17.24			0.37		0.54	0.49			0.11		0.12	0.08	0.20	0.17	0.20							
3-octanone	21.18			0.08		0.18									0.10								
2-octanone	23.00				0.23	0.23	0.61	0.51		0.21		0.04	0.08	0.22	0.08	0.50	0.03				0.08		
3-hydroxy-2-butanone	23.90			0.12						0.06	0.04	0.10		0.19	0.11		0.42	0.27	0.35	0.24	0.22	0.22	0.26
β-ionone	45.60																			0.04			
Total ketones		0.00	0.00	0.56	0.23	0.95	1.11	0.51	0.00	0.38	0.04	0.25	0.16	0.61	0.46	0.69	0.46	0.27	0.35	0.28	0.31	0.22	0.26
Carboxylic acids																							
Acetic acid	30.92		0.19	0.47	0.32	1.19	1.09	0.32		0.50	0.13	1.09	0.39	1.01	0.43	1.27	0.35		0.64	0.16		0.65	0.22
Total carboxylic acids			0.19	0.47	0.32	1.19	1.09	0.32	0.00	0.50	0.13	1.09	0.39	1.01	0.43	1.27	0.35	0.00	0.64	0.16	0.00	0.65	0.22
Furan																							
Furan, 2-pentyl-	19.19			0.03		0.08	0.14			0.05	0.26	0.27	0.19	0.41	0.35		0.05	0.05	0.10			0.34	0.17
Total furans		0.00	0.00	0.03	0.00	0.08	0.14	0.00	0.00	0.05	0.26	0.27	0.19	0.41	0.35	0.00	0.05	0.05	0.10	0.00	0.00	0.34	0.17
Terpene																							
β-ocimene	14.87					0.09																	
Limonene	16.99	1.04	1.06	0.53	2.22	0.92	0.71	2.25	1.51	0.45	0.89	0.81	0.94	1.79	0.89	2.20	2.03	0.10	1.93	0.35	1.34	1.45	0.52
1,8-cineole	17.96			2.64								0.25				1.70							
p-cymene	21.67																						
α-terpineol	40.87																						
E-Citral	41.87																0.13						
Total terpenes		1.04	1.06	3.16	2.22	1.01	0.71	2.25	1.51	0.45	0.89	1.06	0.94	1.79	0.89	3.90	2.16	0.10	1.93	0.35	1.34	1.45	0.52
Other																							
m-xylene	14.82	0.69	0.25	0.06	0.39	0.23	0.20	0.22	0.42	0.09	0.16	0.17	0.19	0.41	0.32	0.33	0.49	0.11	0.77	0.26	0.25	0.35	0.09
Total others		0.69	0.25	0.06	0.39	0.23	0.20	0.22	0.42	0.09	0.16	0.17	0.19	0.41	0.32	0.33	0.49	0.11	0.77	0.26	0.25	0.35	0.09

A – alginate, B – chitosan, C – gellan gum, D – gum arabic, E – High shine, F – Sta-fresh, G – control.

Table 2. Attributes used to describe the sensory profile of 'African Delight™' plums in the sensory analysis, including the descriptors, standards and scores assigned by the panel per standard during the training sessions

Attribute	Specific attribute	Scale	Standard	Reference standard score
Aroma	Plum	0=none, 100=prominent	Ripe 'African Delight™' plum	70
	Green	0=none, 100=prominent	Cis-3-hexenol (0.1% v/v)	50
	Fermented	0=none, 100=prominent	Ethanol (5% v/v)	60
Appearance	Peel	0=light, 100=dark	Pictures of plum (Fig. 5, Appendix)	(a) 0-25, (b) 25-50, (c) 50-75, (d) 75-100
	Flesh	0=opaque, 100=translucent	Pictures of plum (Fig. 6, Appendix)	(a) 30, (b) 60, (c) 90
Flavour	Plum	0=none, 100=prominent	Ripe plums of different cultivars ('African Delight™', 'Angeleno', 'Ruby Star')	70
	Unripe	0=none, 100=prominent	Unripe plum	40
	Overripe	0=none, 100=prominent	Prunes	80
	Fermented	0=none, 100=prominent	Ethanol (2% v/v)	40
Taste	Sweetness	0=low, 100=high	Sucrose (5% w/v)	50
	Sourness	0=low, 100=high	Citric acid (0.2% w/v)	60
Texture	Firmness	0=firm, 100=soft	Unripe plum, canned peach	80
	Melting	0=low, 100=high	Canned peach	50
	Juiciness	0=low, 100=high	Spanspek	80

Table 3. Preliminary trials to establish coating formulations for Research Paper 1 on 'Laetitia' plums stored at 20°C for seven days

Edible coating	Formulation	Weight loss (g) at end of storage	Key Findings
Alginate (2% CaCl supplementary dip)	1% alginate*	10.95	
	2% alginate*	7.80	
	3% alginate*	6.11	
	3% alginate, 1% oil	2.33	Lowest weight loss with 2% alginate with 2% oil
	2% alginate, 1% oil	2.05	
	2% alginate, 2% oil	1.45	
	2% alginate, 1% glycerol, 2% oil	2.38	
Chitosan (dissolved in 0.5% acetic acid)	1.5% chitosan, 0.05% Tween-20**	4.46	
	1.5% chitosan, 0.05% Tween-20, 1% oil**	5.22	Lowest weight loss with 1.5% chitosan and 0.05% Tween-20
	2% chitosan, 0.05% Tween-20, 1% oil**	4.94	
Gellan gum	0.5% gellan gum, 1% glycerol	1.68	
	1% gellan gum, 1% glycerol	1.94	Lowest weight loss with 0.5% gellan gum, 1% glycerol, 1% oil, however, coating was grainy. Addition of Tween-20 helped reduce graininess and did not affect weight loss significantly.
	0.5% gellan gum, 1% glycerol, 1% oil	1.21	
	1% gellan gum, 1% glycerol and 1% oil	1.40	
	0.5% gellan gum, 1% glycerol, 1% oil, 0.1% Tween-20	1.29	
Gum arabic	10% gum arabic, 1% glycerol, 1% oil	2.34	
	3% gum arabic, 1% glycerol, 1% oil	1.29	
	2% gum arabic, 1% glycerol, 1% oil	1.23	Lowest weight loss with 2% gum arabic, 1% glycerol, 1% oil
	2% gum arabic, 1% glycerol and 0.5% oil	1.45	
	2% gum arabic, 1% glycerol, 1% oil, 0.1% Tween-20	1.46	
Methyl cellulose	3% methyl cellulose, 1.5% glycerol*	8.01	
	2% methyl cellulose, 1% glycerol*	7.53	Lowest weight loss with 2% methyl cellulose, 1% glycerol, 1% oil; however, coating was very bubbly and grainy, thus was not considered for main trial.
	2% methyl cellulose, 1% glycerol, 0.5% oil*	7.30	
	2% methyl cellulose, 1% glycerol, 1% oil	2.35	

* 'Ruby Sun' plums used in trial

** 'Lady Red' plums used in trial

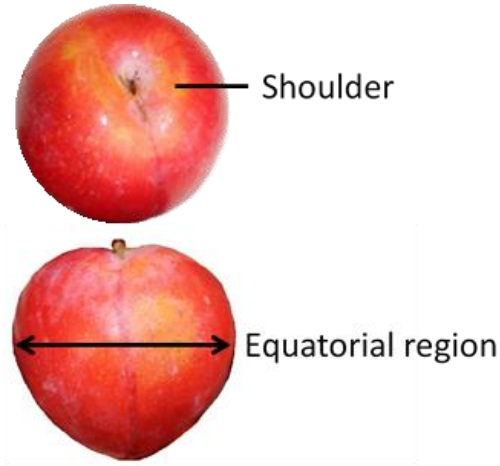

Figure 1. Shoulder and equatorial region of plum.

Figure 2. A shrivelled ‘African Delight™’ plum.

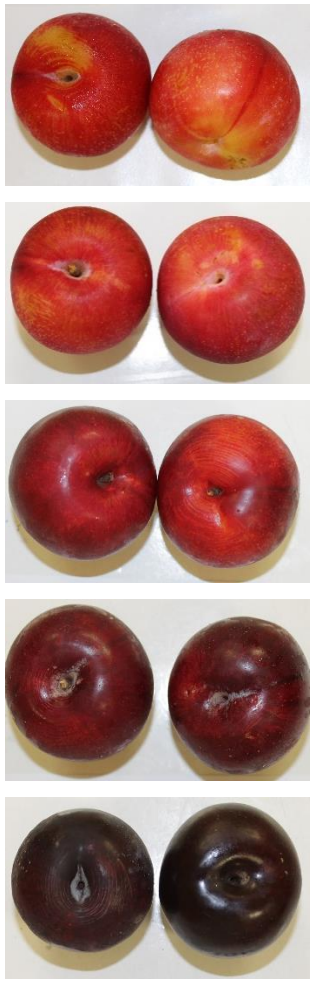

Figure 3. Peel colour changes of ‘African Delight™’ plums throughout ripening.

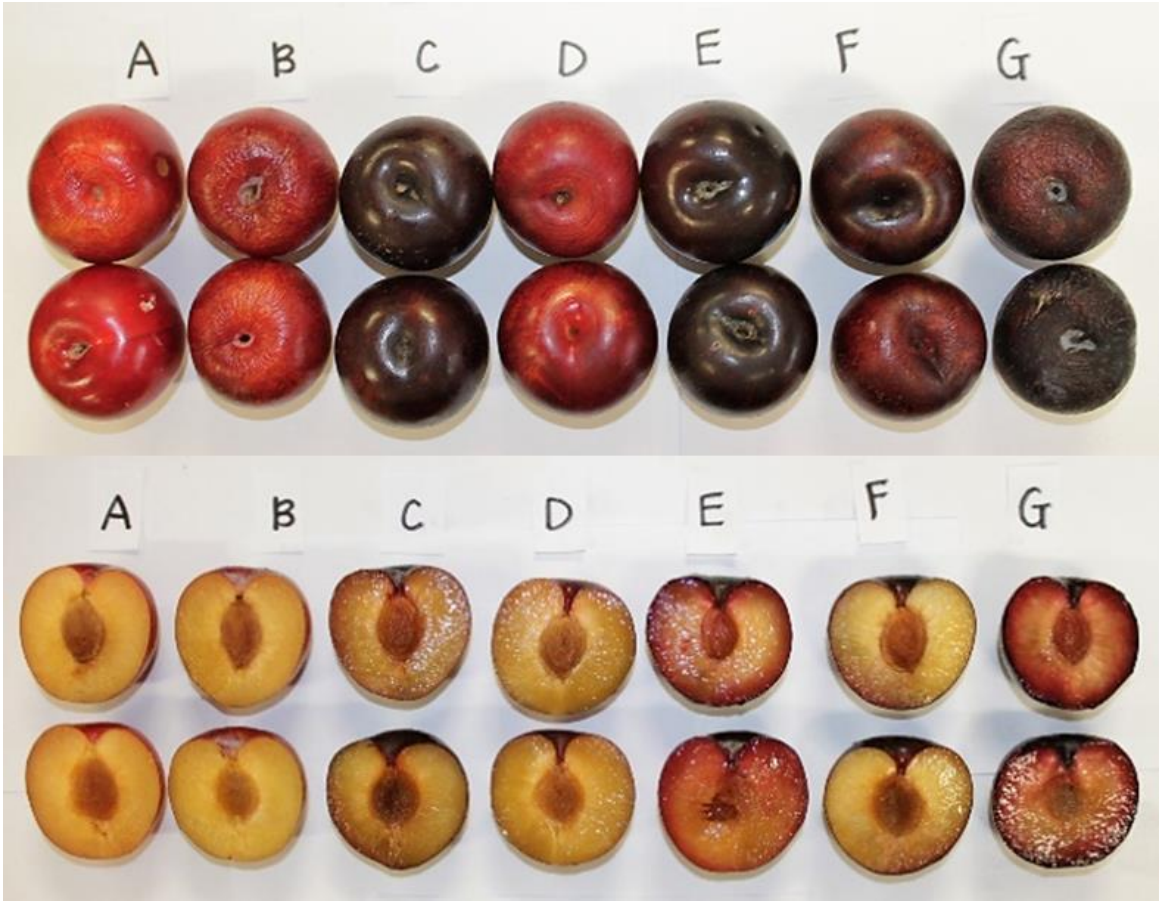

Figure 4. Peel and flesh colour of ‘African Delight™’ plums after 20 d shelf life.

A – alginate, B – chitosan, C – gellan gum, D – gum arabic, E – High shine, F – Sta-fresh, G – control.


(a)


(b)


(c)


(d)

Figure 5. Images used to describe peel colour in sensory analysis of ‘African Delight™’ plums.


(a)


(b)

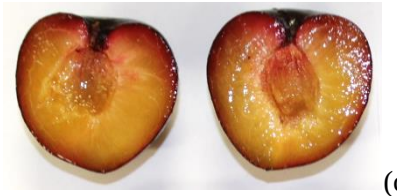
(c)

Figure 6. Images used to describe flesh colour in sensory analysis of ‘African Delight™’ plums.